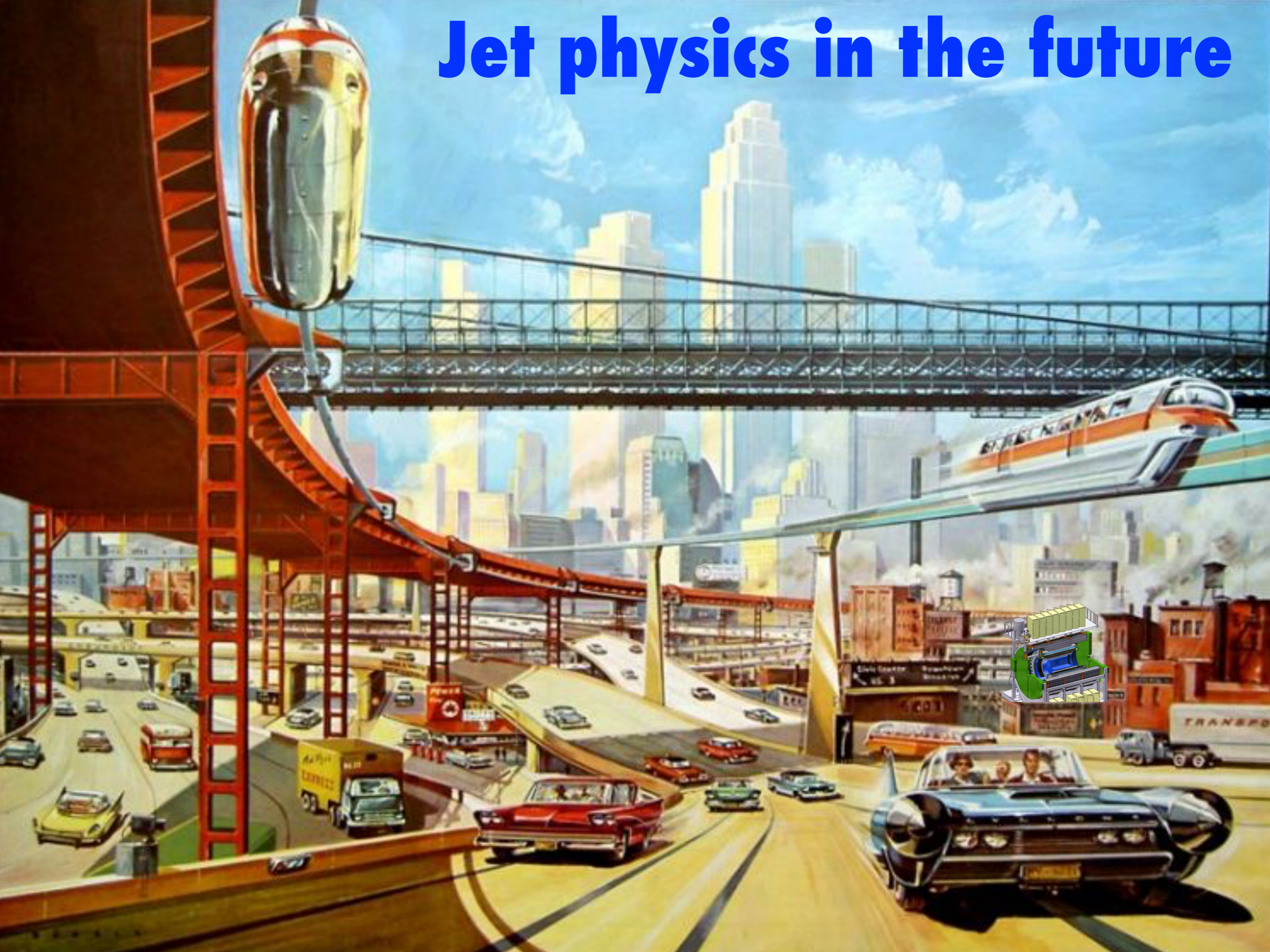


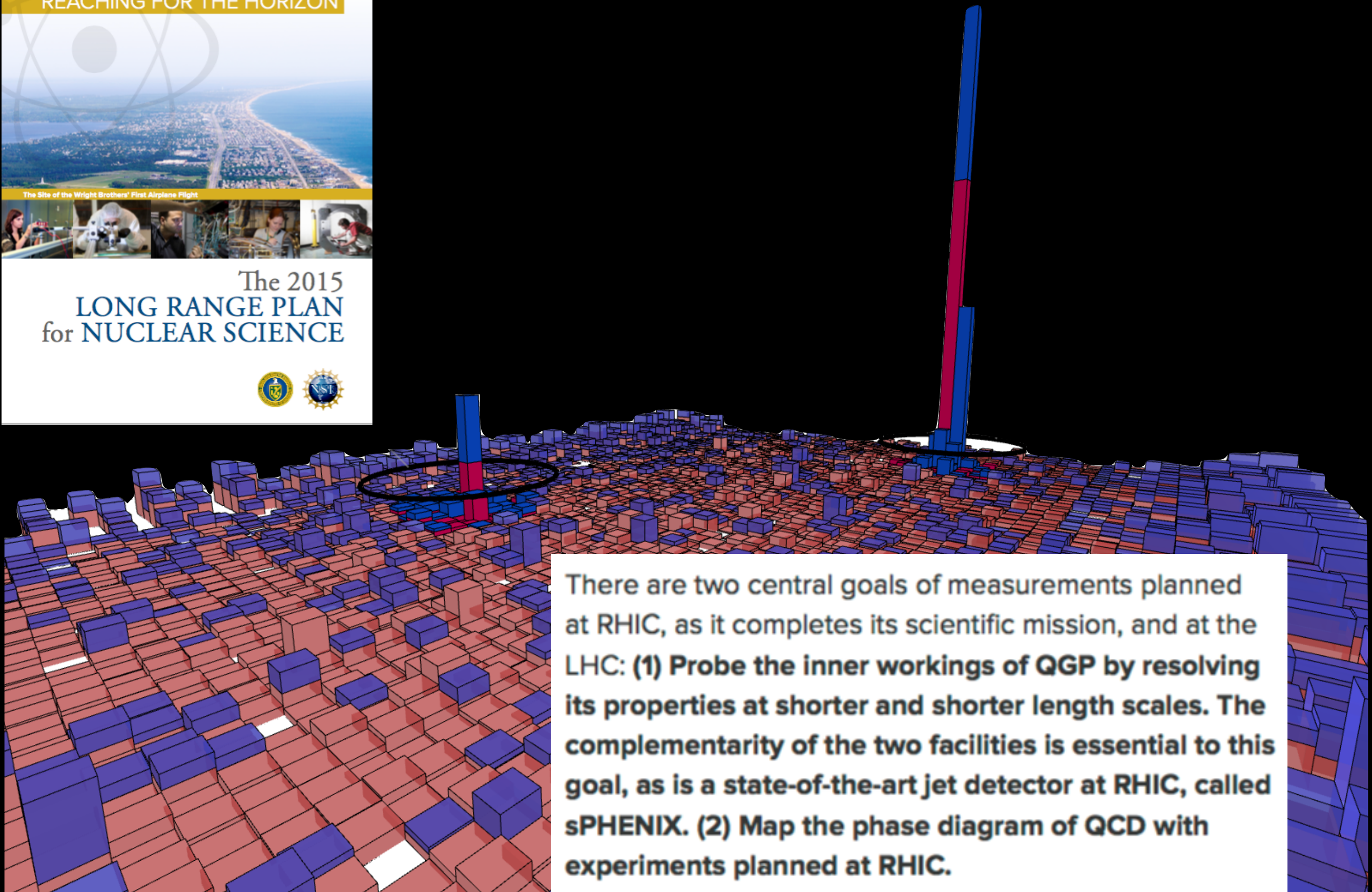
Jet physics in the future



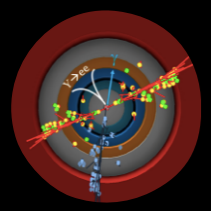
REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

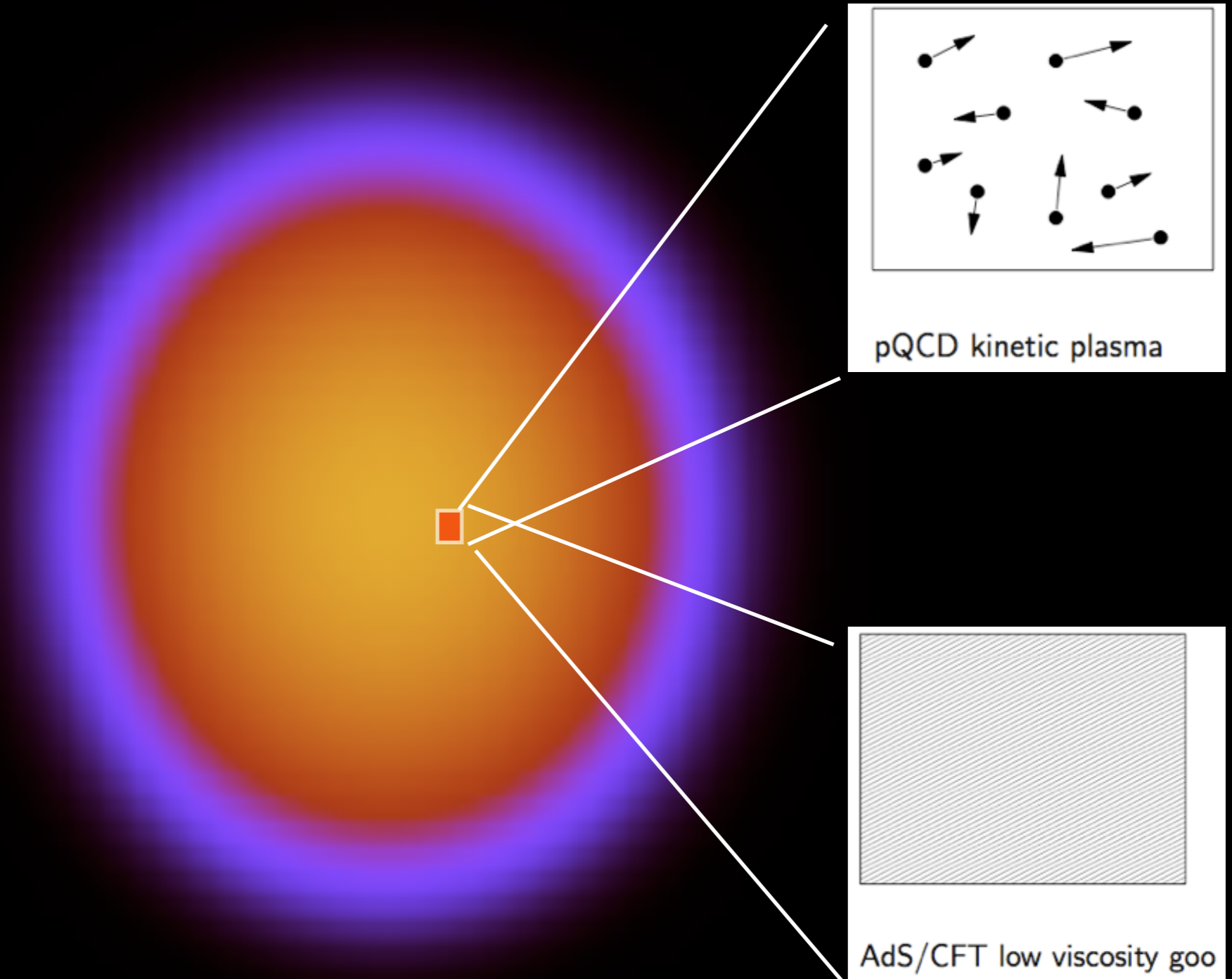
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



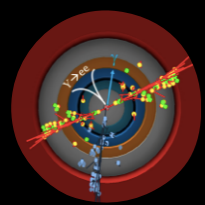
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**



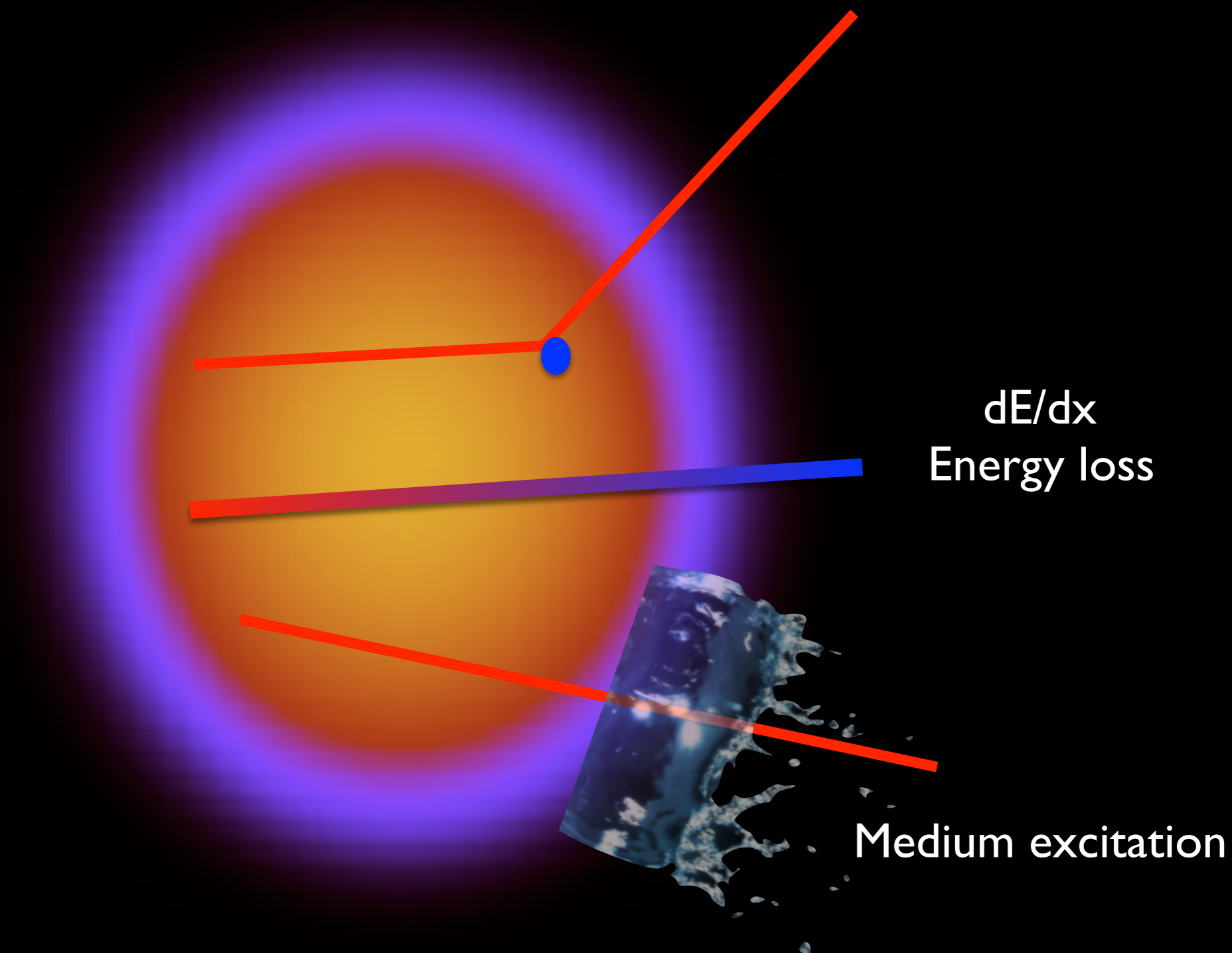
The inner workings of the QGP



from Thomas Schafer

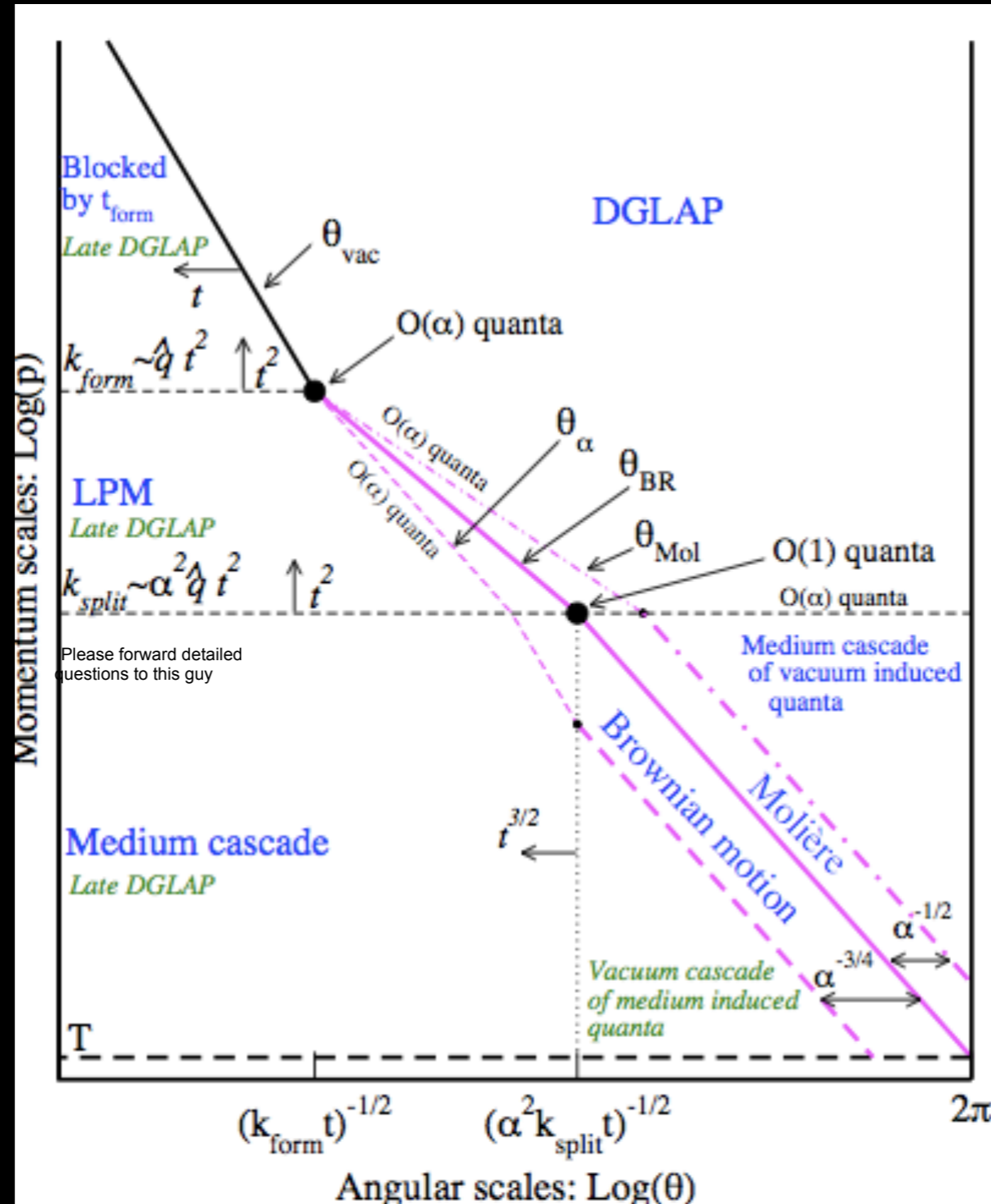


Rutherford Scattering



Angular and momentum structure of intra-jet parton cascade

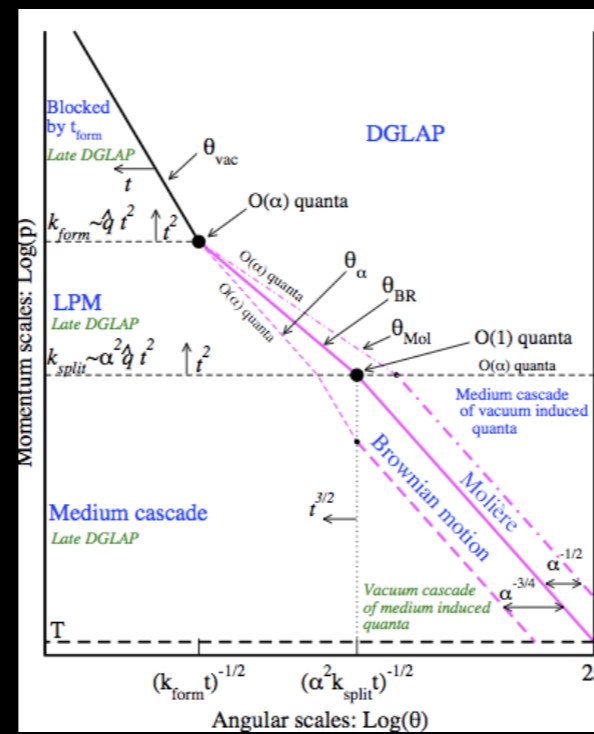
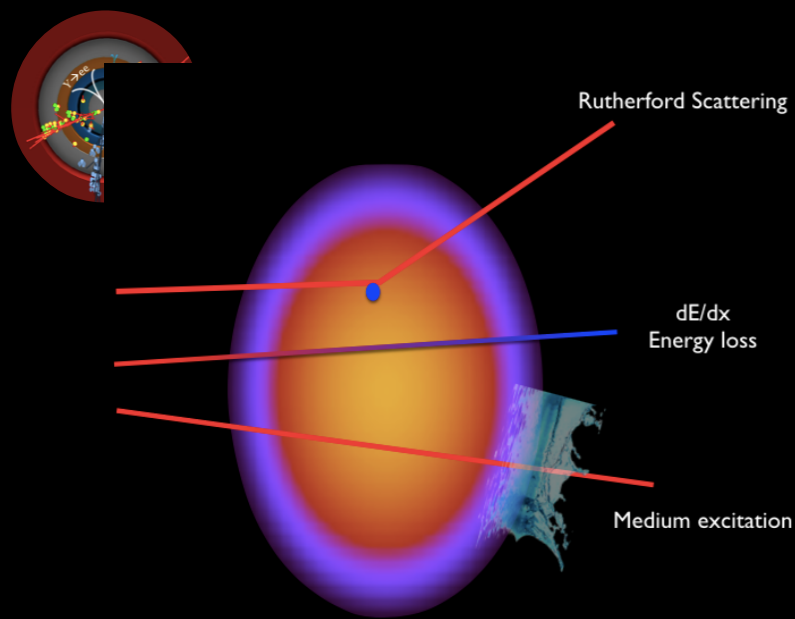
Kurkela,
Wiedemann,
arXiv:1407.0293



Jets evolve in angular and momentum space

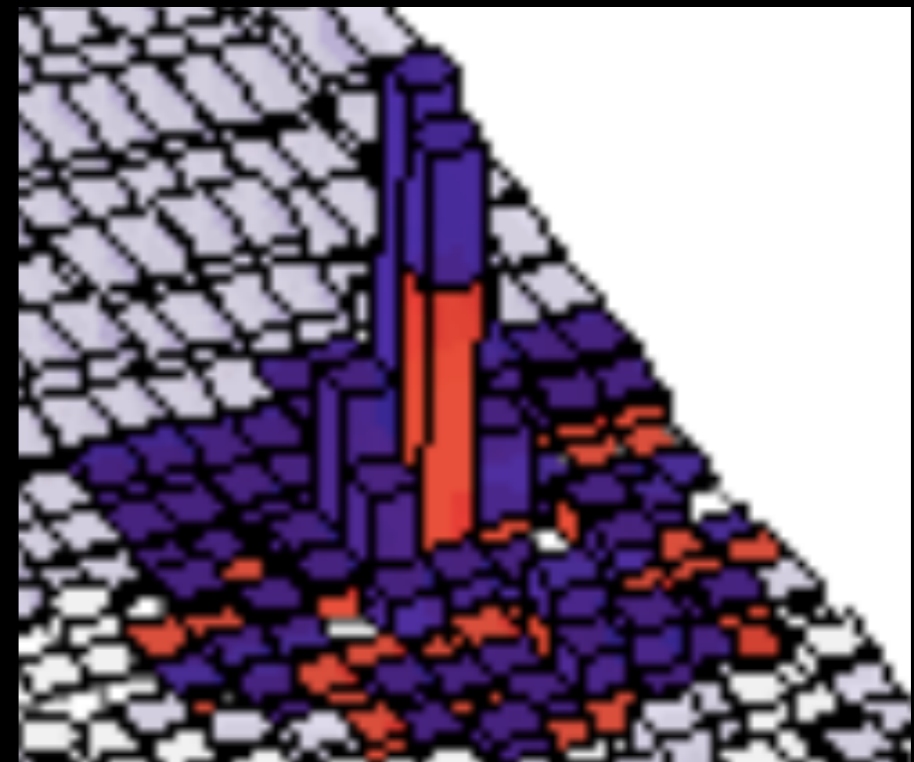
At different scales, evolution is dominated by different mechanisms:

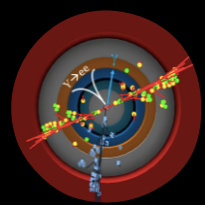
- vacuum evolution
- (jet-constituent)-medium scattering
- in-medium cascade



“Jets” have angular, momentum and temporal structure that is modified as they evolve in the medium

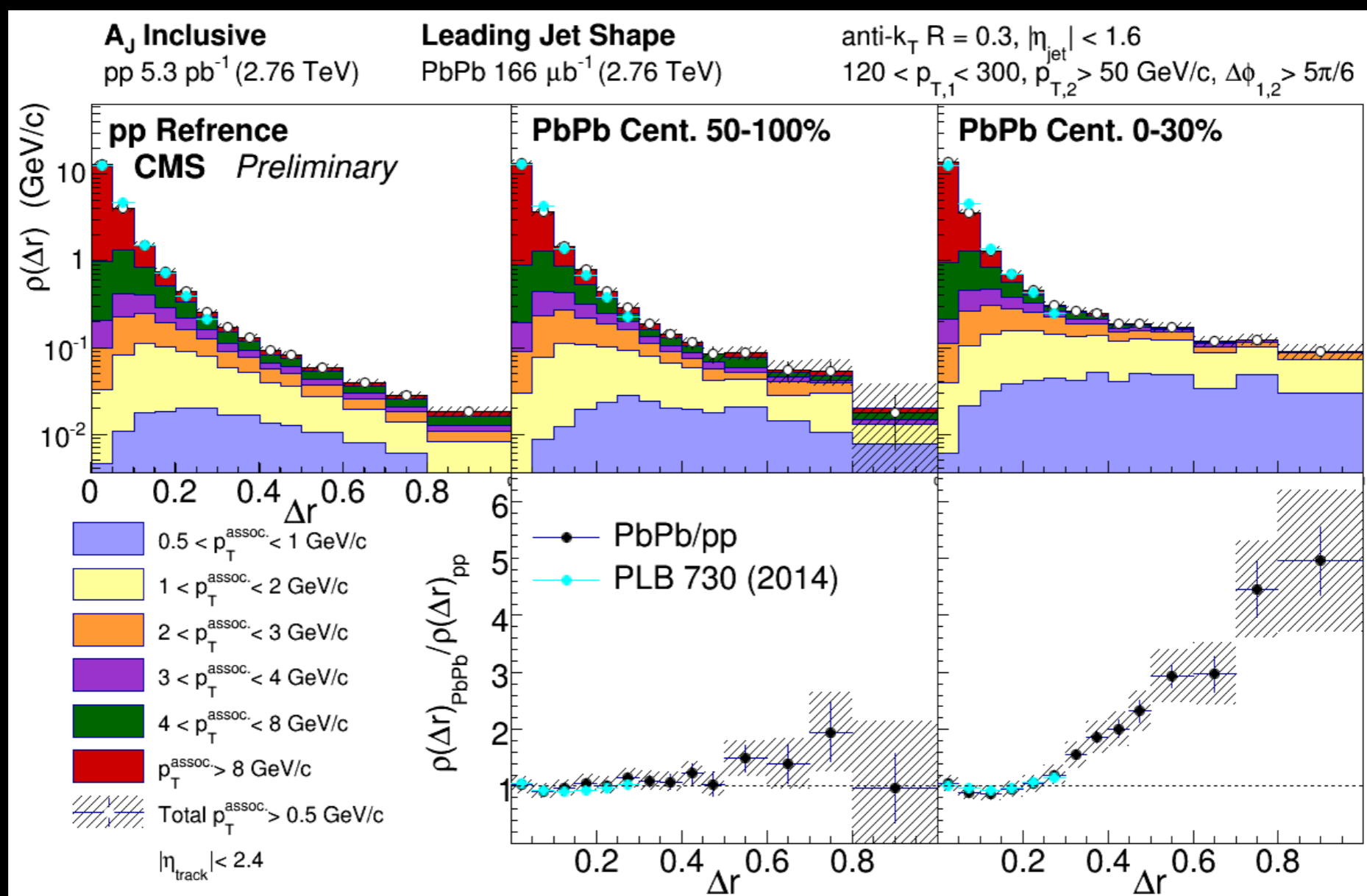
Results are final state hadron showers with jet-by-jet correlated changes of their angular and momentum structure



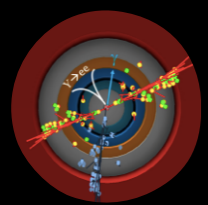


Information about what happens to the shower *on average* can be summarized in correlation functions*...

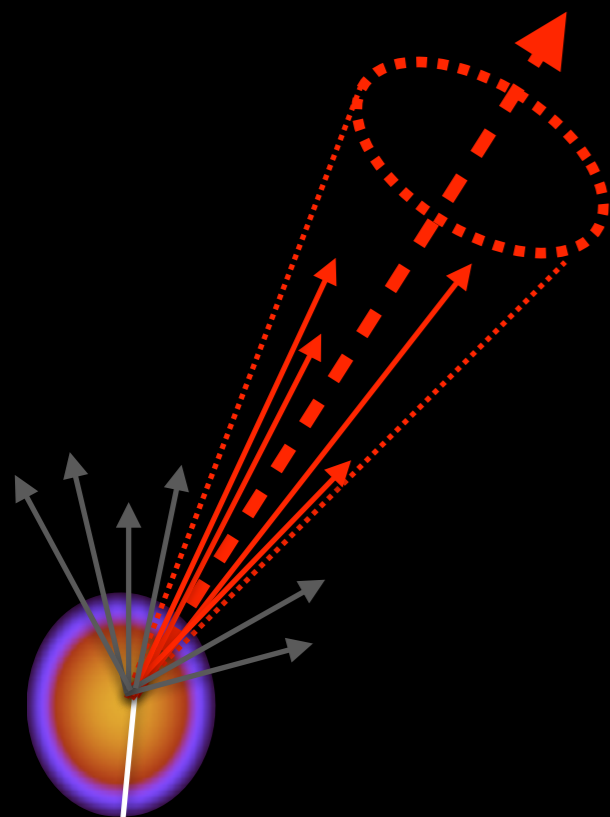
*jet-track, but more generally angular + momentum correlations of jet constituents



...in particular if jet finding biases are eliminated



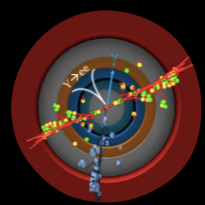
Another emerging theme



Use away-side and/or same side tags to systematically control jet system:

- Initial parton energy, flavor: Z and γ tag
- Geometry: hadron vs jet vs Z/ γ tag
- parton flavor/mass: D, B, c/b-tag, displaced J/ ψ

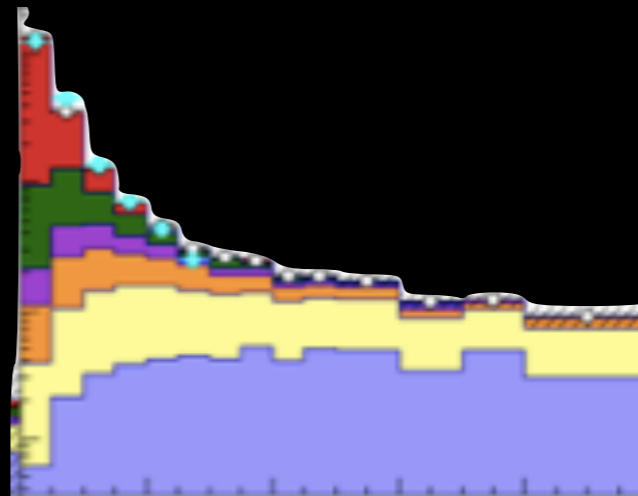
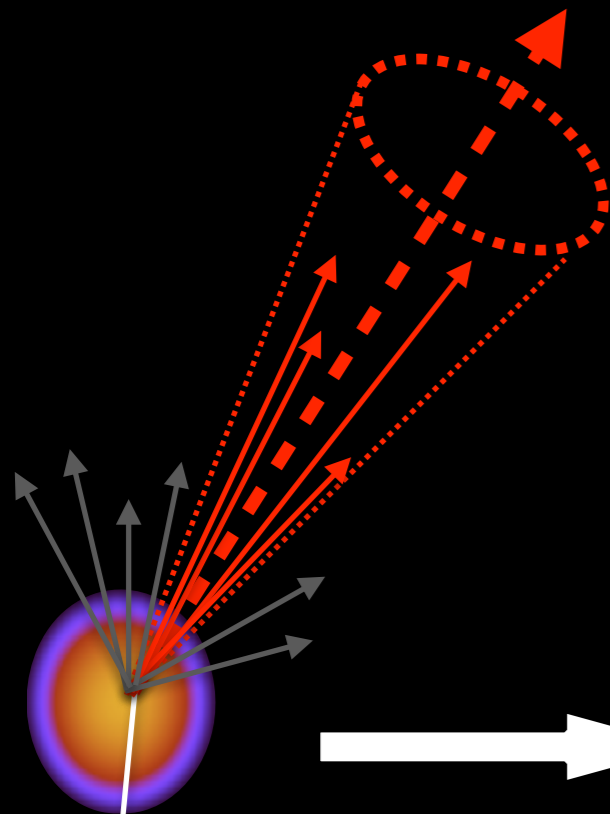
Also, rapidity dependence to control flavor



Another emerging theme

Use charged tracks (and/or calo-based constituents) to characterize momentum flow relative to jet system

- Integrate to traditional jet shapes, fragmentation func's
- In-cone vs out-of-cone energy distributions
- Jet-substructure and jet-by-jet classifiers

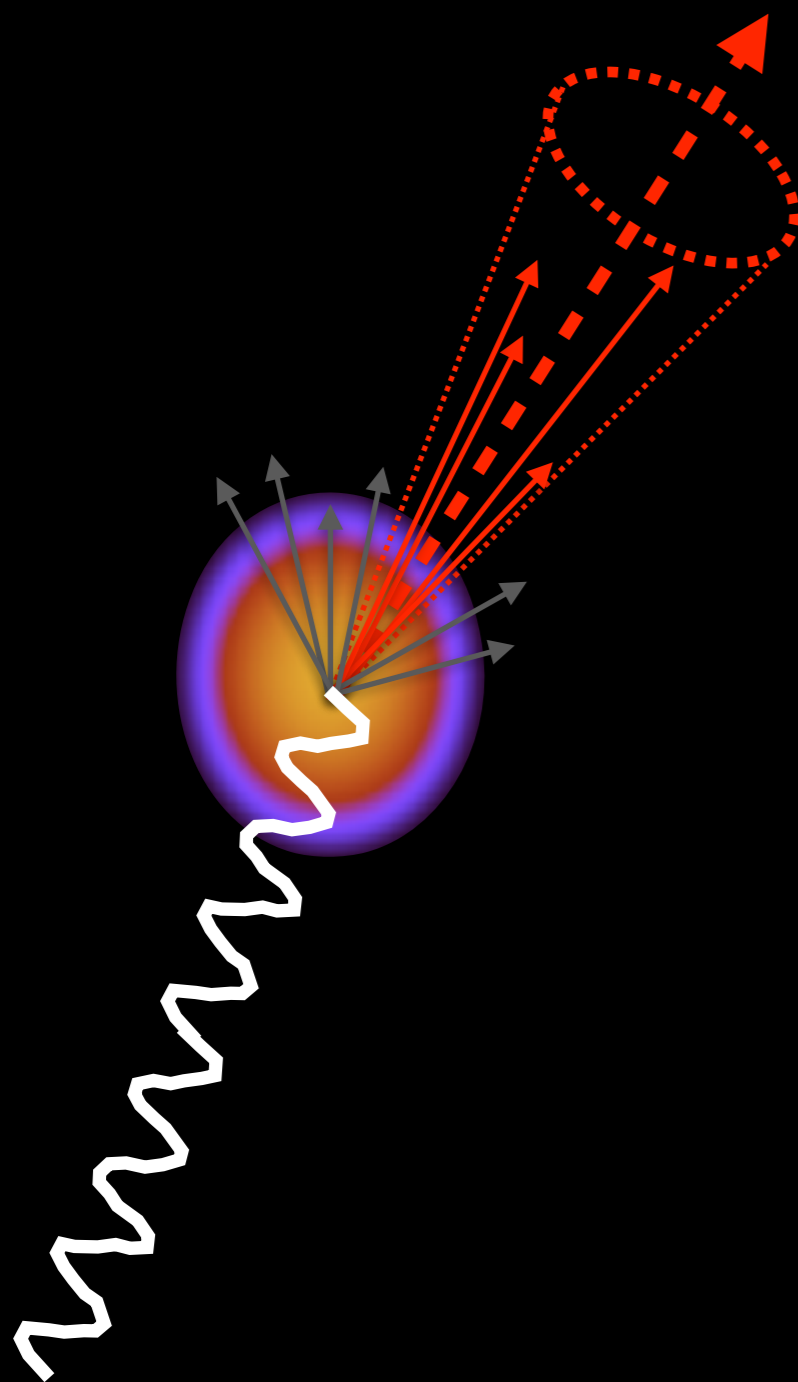
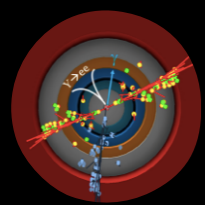


$$C_2(p_T, \Delta\eta, \Delta\phi, \dots)$$

Use away-side and/or same side tags to systematically control jet system:

- Initial parton energy, flavor: Z and γ tag
- Geometry: hadron vs jet vs Z/ γ tag
- parton flavor/mass: D, B, c/b-tag, displaced J/ ψ

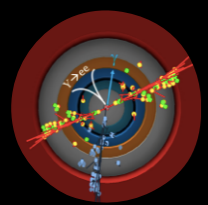
Also, rapidity dependence to control flavor



My personal favorite: Z +jet and γ +jet

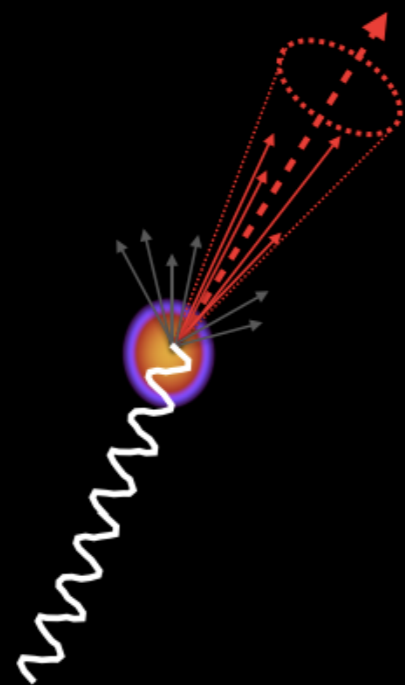
(or more specifically: angular and momentum distributions of associated charged particles wrt to the jet axis in V +jet events)

- remove jet energy scale uncertainty
- remove UE and v_n bias on jet selection
- (potentially) remove jet finding bias
- *select on initial parton, not final state shower properties*

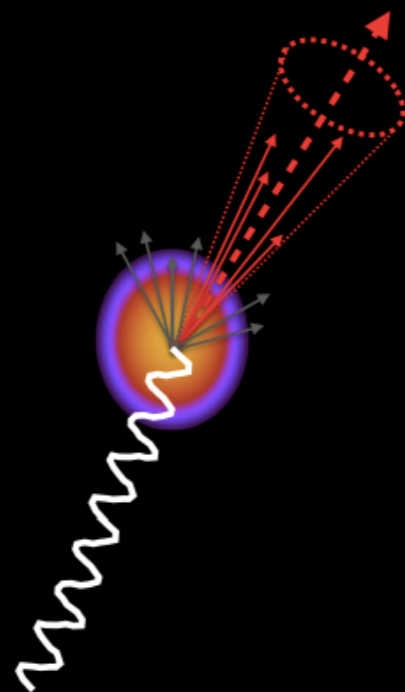


Jet shower modifications for ^{nearly} identical partons in the RHIC and LHC plasmas and vacuum

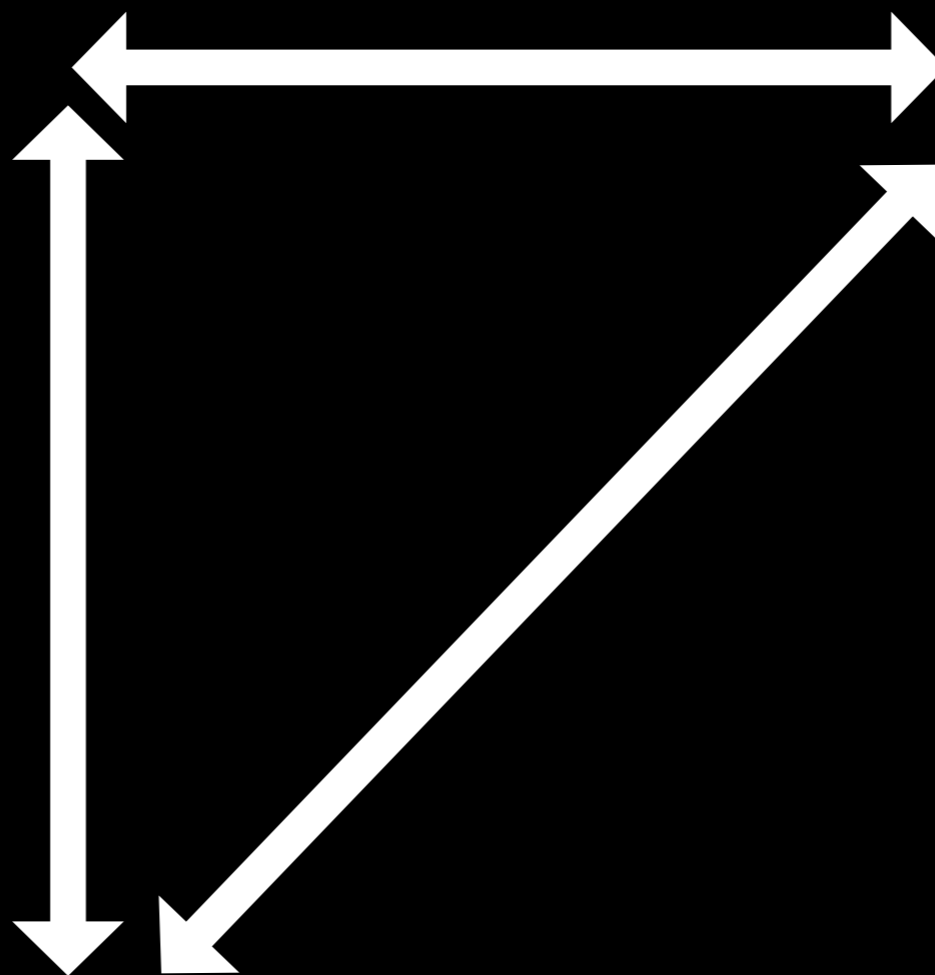
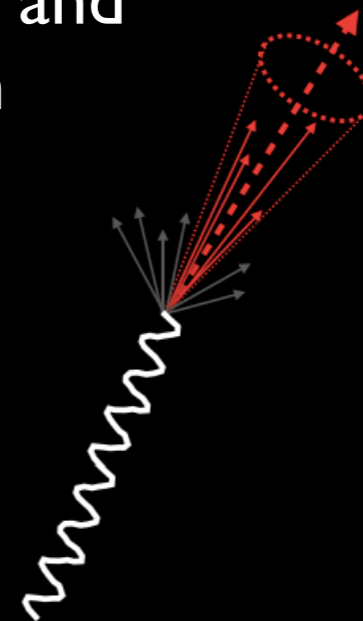
RHIC-QGP

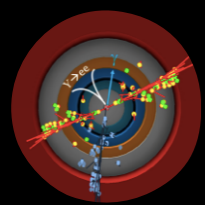


LHC-QGP



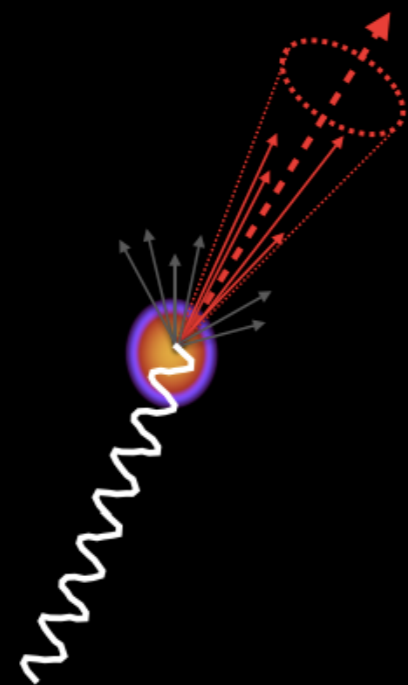
$p+p$



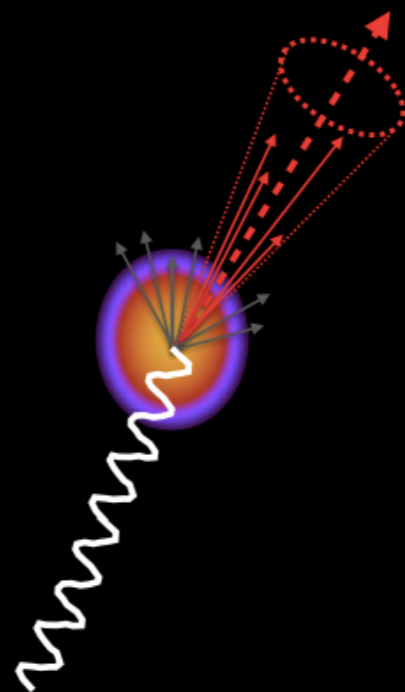


Jet shower modifications for ^{nearly} identical partons in the RHIC and LHC plasmas and vacuum

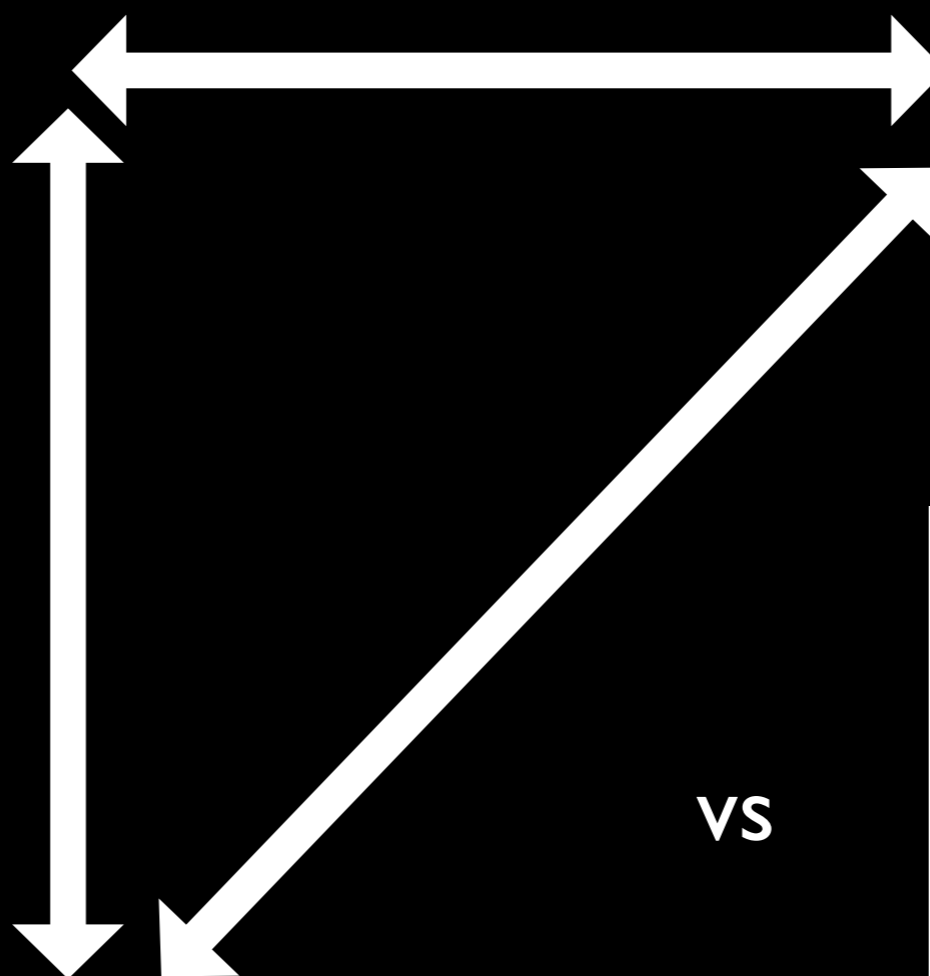
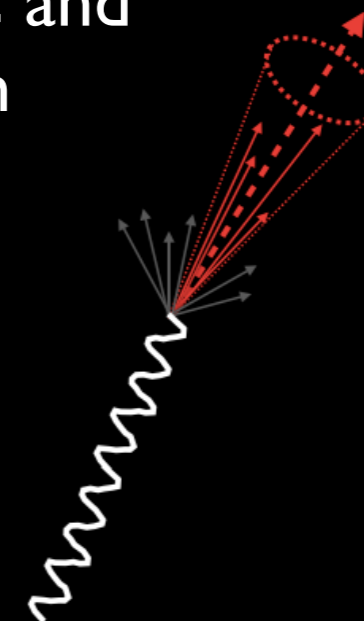
RHIC-QGP



LHC-QGP

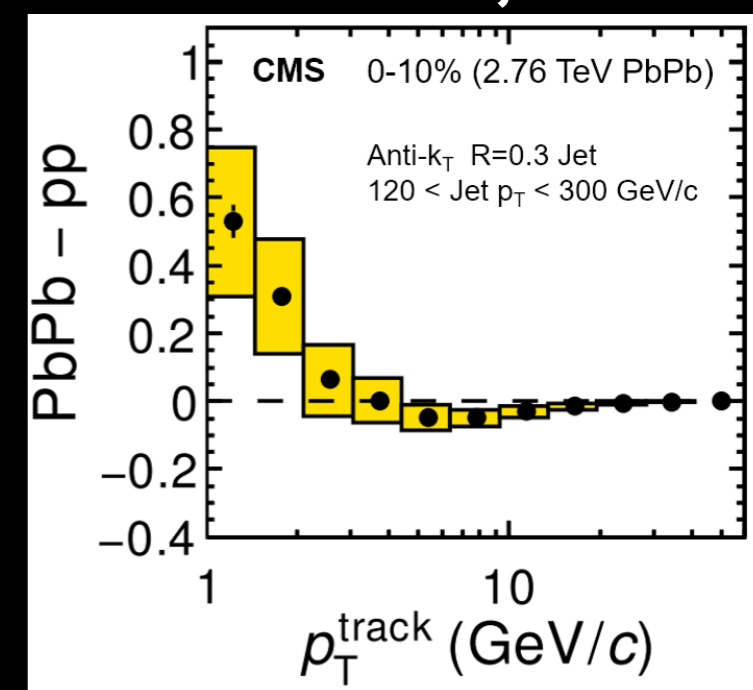


p+p

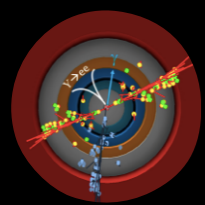


vs

inclusive jet FF

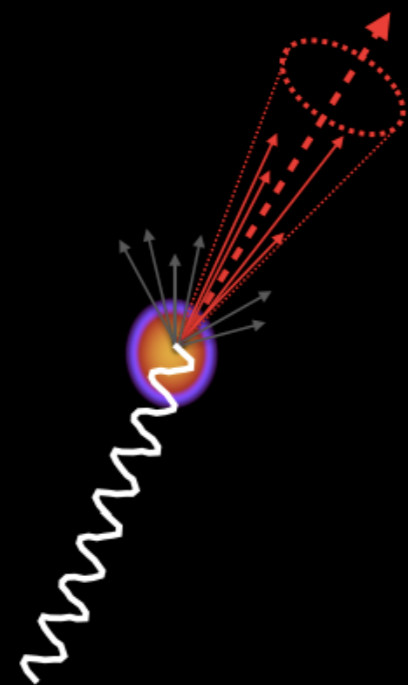


different initial parton p_T and flavor distributions in numerator and denominator

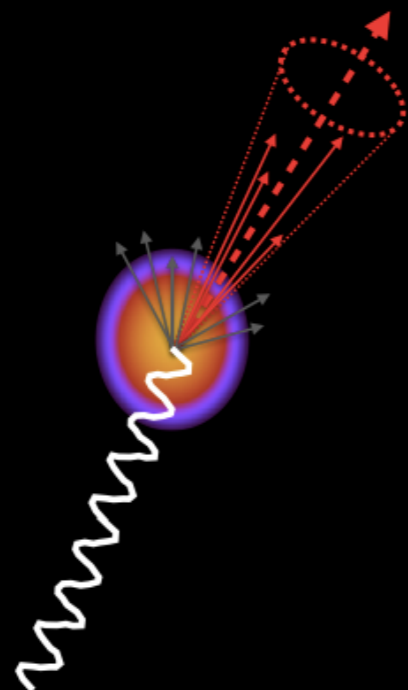


Jet shower modifications for ^{nearly} identical partons in the RHIC and LHC plasmas and vacuum

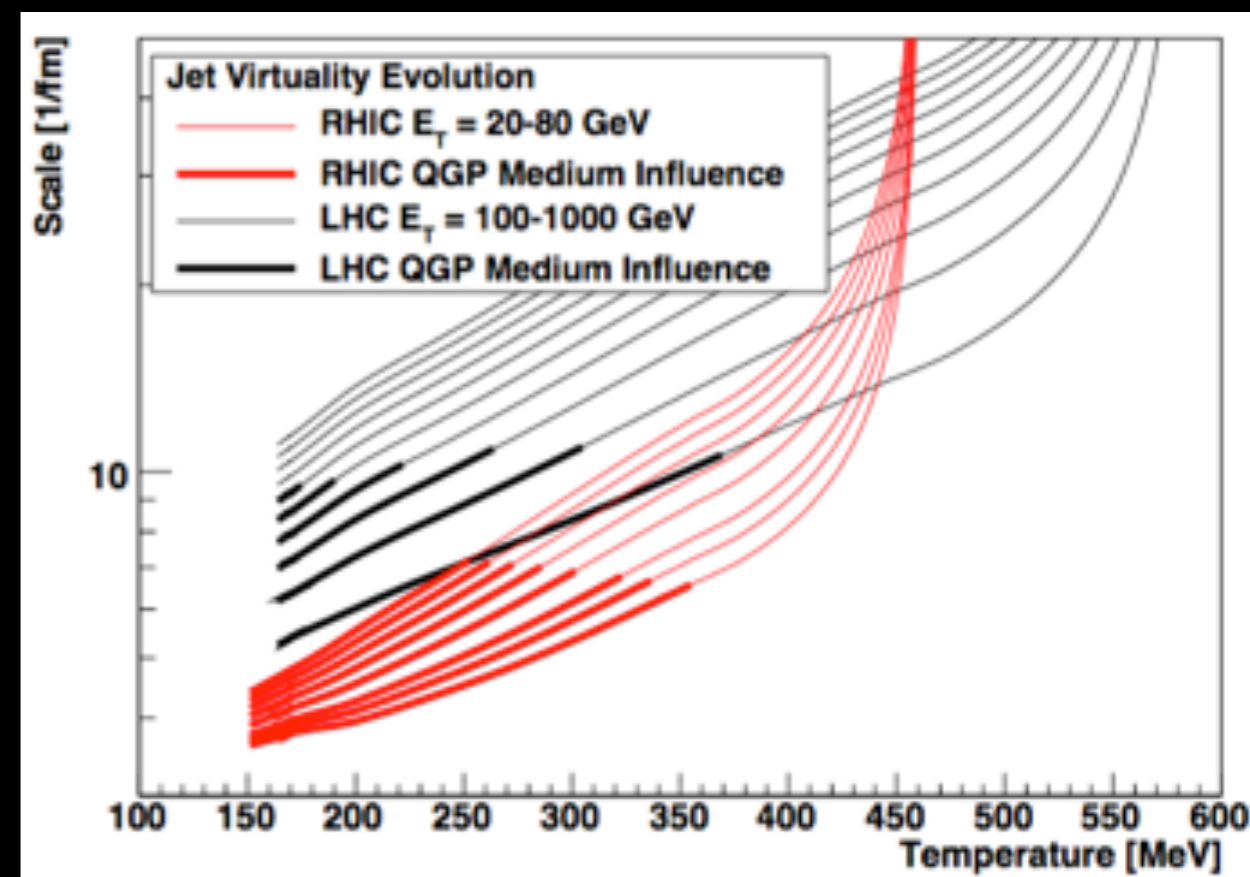
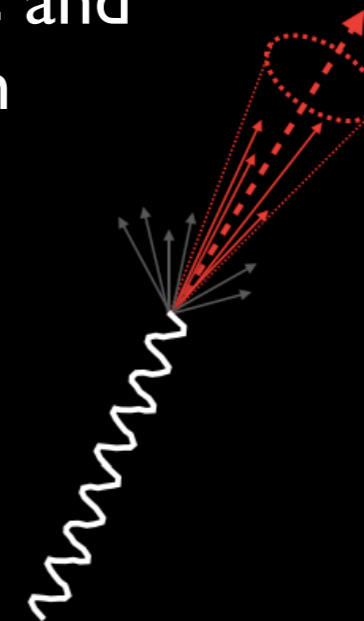
RHIC-QGP

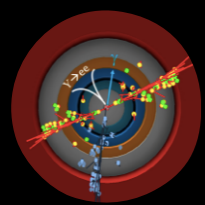


LHC-QGP



p+p





Jet shower modifications for ^{nearly} identical partons in the RHIC and LHC plasmas and vacuum

RHIC-QGP

$p+p$

Need very high rate and large acceptance tracking and calorimetry

LHC-QGP

Future Heavy Ion Jet experiments

RHIC

LHC



Species: Au+Au (or PbPb?!)

Energy $\sqrt{s_{NN}} = 0.2\text{TeV}$

Collision rate ($\pm 10\text{cm}$): 15+kHz

Data taking: 2022-2024

New detector: sPHENIX

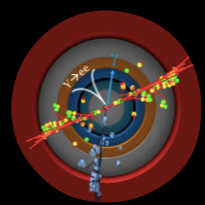
Species: PbPb (or Au+Au?!)

Energy $\sqrt{s_{NN}} = 5.\text{xTeV}$

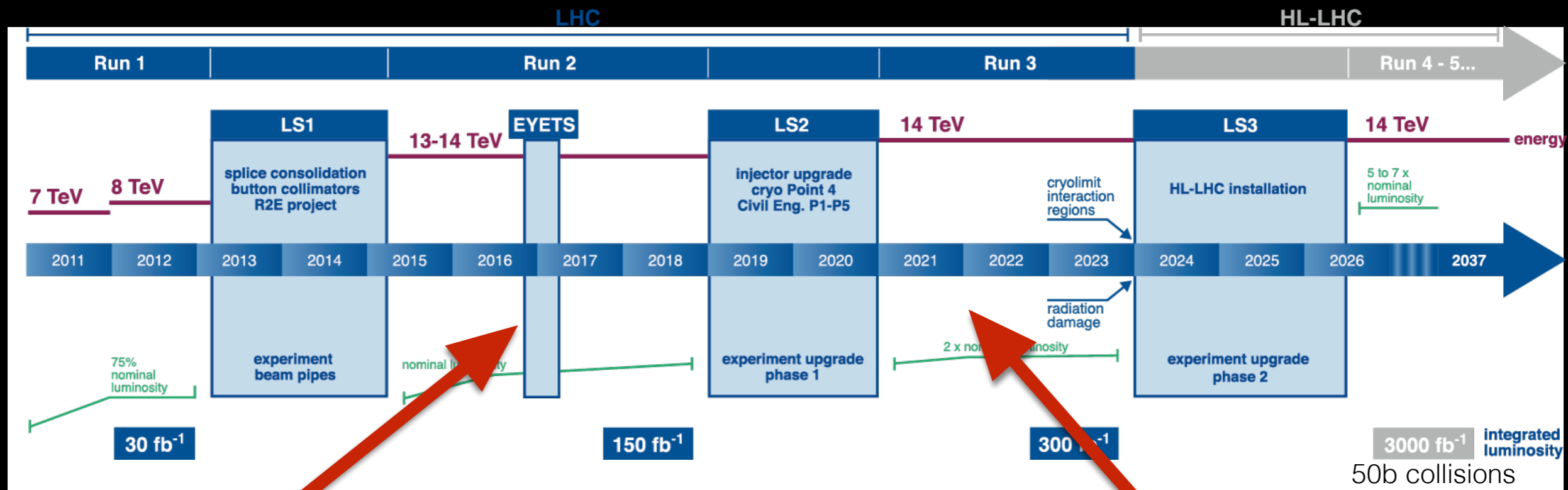
Collision rate ($\pm 15\text{cm}$): 20-50kHz

Data taking: 2015-2018, 2021-2023,...

ALICE, ATLAS, CMS upgrades



LHC / HL-LHC Plan



PbPb in Run 2

$$\sqrt{s} = 5\text{TeV}$$

Collision rate $\approx 20\text{kHz}$

$$L_{\text{int}} \approx 0.5/\text{nb} \text{ (2015)}$$

$$1.5/\text{nb} \text{ (2018)}$$

PbPb in Run 3

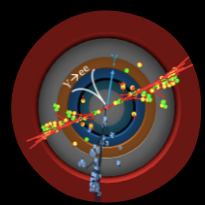
$$\sqrt{s} = 5-5.5\text{TeV}$$

Collision rate $\approx 50\text{kHz}$

$$L_{\text{int}} \approx 10/\text{nb} \text{ (run 2+3)}$$

CMS/ATLAS collected 0.5 nb^{-1} in '15
i.e., about 5% of Run 2+3 total,
factor 10 wrt Run 1 in HP stat's

Run 2 + 3 vs LHC Run 1: x60 due to higher luminosity; x3 due to higher \sqrt{s}

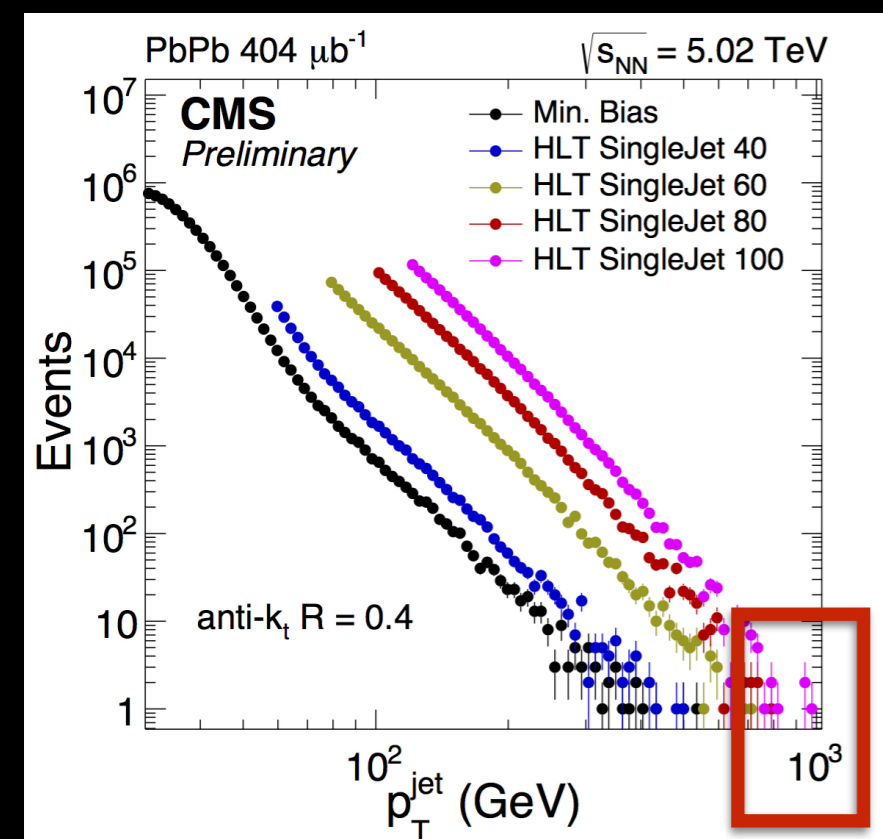
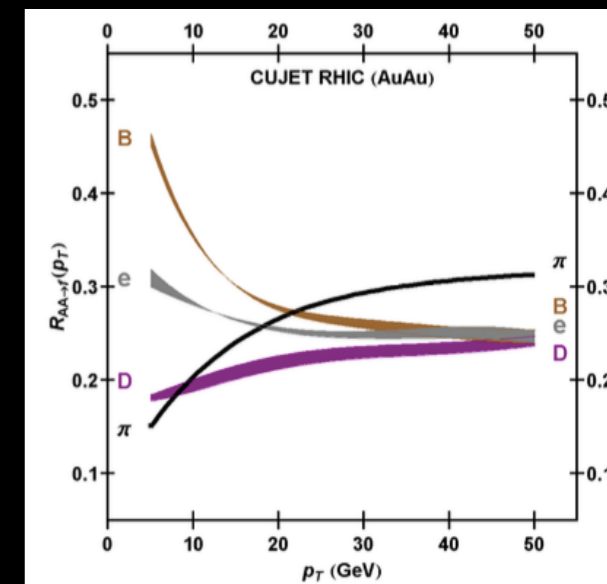


LHC projection

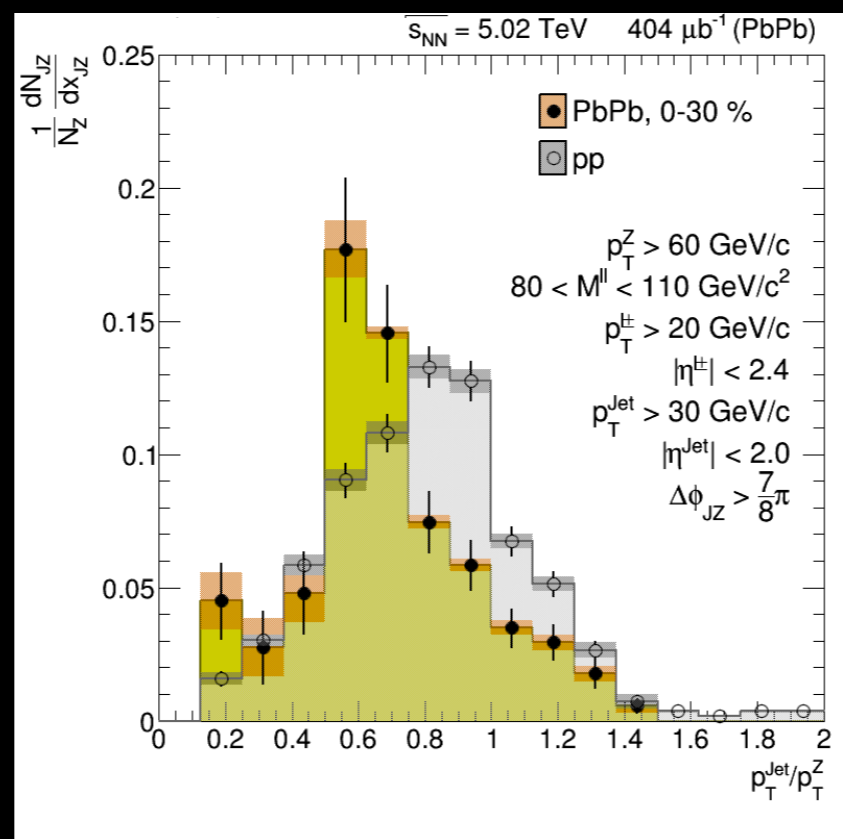
~confirmed by 2015 data

	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	$\sim 10\text{M}$
b-jet ($p_T > 120$ GeV/c)	~ 500	$\sim 140\text{k}$
Isolated γ ($p_T^\gamma > 60$ GeV/c)	$\sim 1.5\text{k}$	$\sim 300\text{k}$
Isolated γ ($p_T^\gamma > 120$ GeV/c)	—	$\sim 10\text{k}$
W ($p_T^W > 50$ GeV/c)	~ 350	$\sim 70\text{k}$
Z ($p_T^Z > 50$ GeV/c)	~ 35	$\sim 7\text{k}$

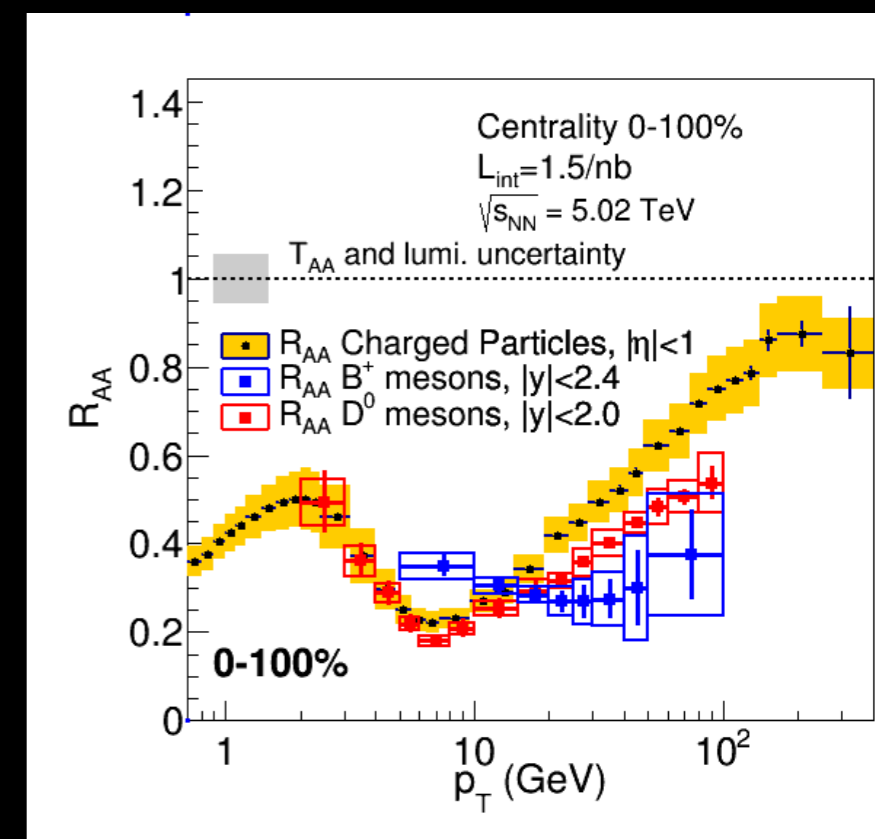
CUJET



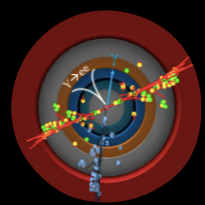
Run 3 expectation: 10% R_{AA} @ ~1 TeV



Run 2 **projection**: Z+jet

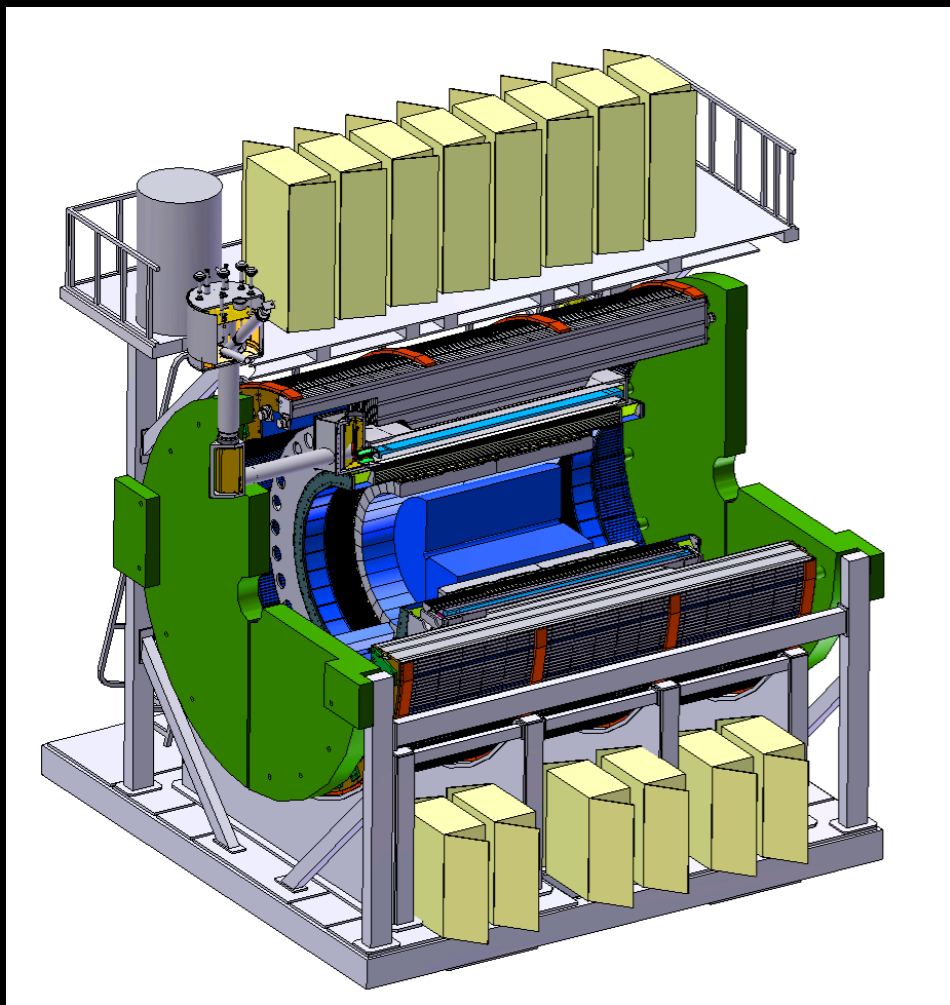


Run 2 **projection**: h^\pm , D and B R_{AA}
Run 3: x5 in data



sPHENIX?

sPHENIX \es-'fē-niks\: A high-rate capable detector at RHIC IP8, built around the former BaBar 1.5 T superconducting solenoid, with full electromagnetic and hadronic calorimetry and precision tracking and vertexing, with a core physics program focused on light and heavy-flavor jets, direct photons, Upsilon and their correlations in p+p, p+A, and A+A to study the underlying dynamics of the QGP – physics delivered by 22 weeks of Au+Au, 10 weeks each of p+p and p+A (@ 200 GeV).



Emerged from 2010 decadal planning process
Science review in early 2015

Director's cost&schedule review Nov 2015

Science collaboration formed by Dec 2015

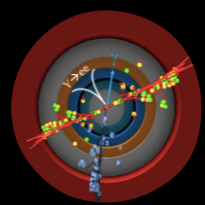
(Co-spokespeople '16-'19: Dave Morrison & GR)

CD0: Early 2016

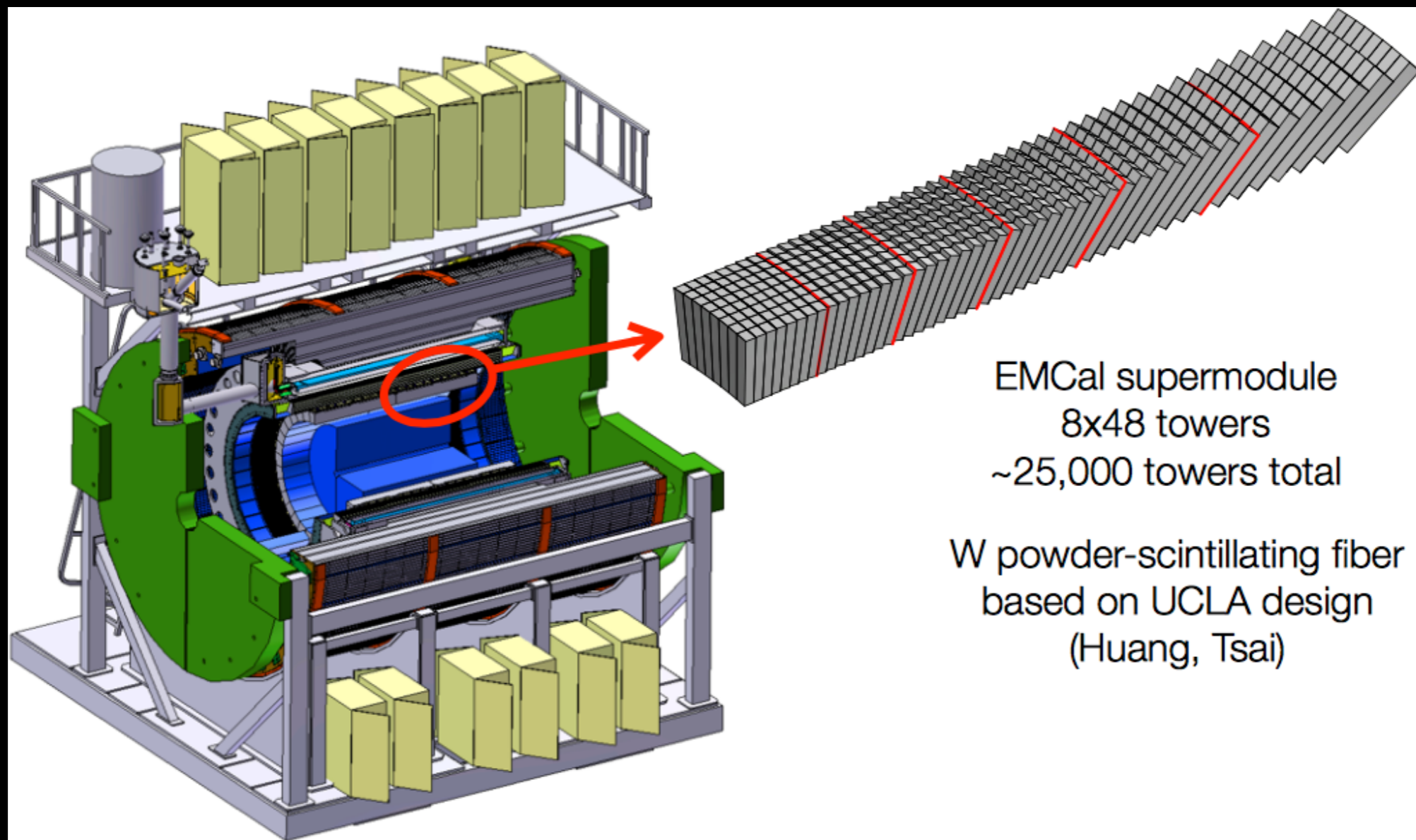
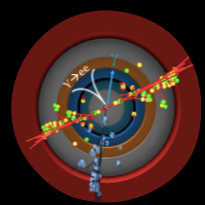
1st run: Early 2022

60 Institutions

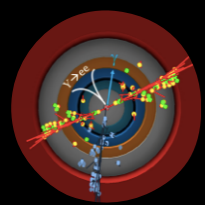
200 collaborators (→500)



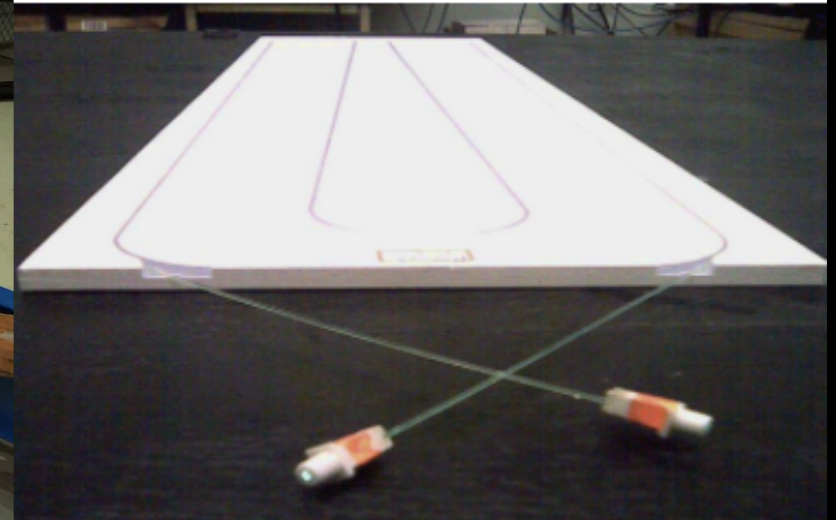
BaBar 1.5T solenoid passed low-power cold test at BNL a few weeks ago



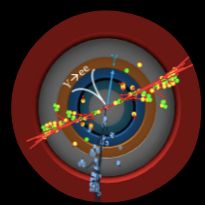
Prototyping of subdetector technologies underway



scintillator readout
via imbedded fibers
bundled together
and read by a SiPMs
and waveform digitizers



Calorimeter modules in FNAL beam test April 2016

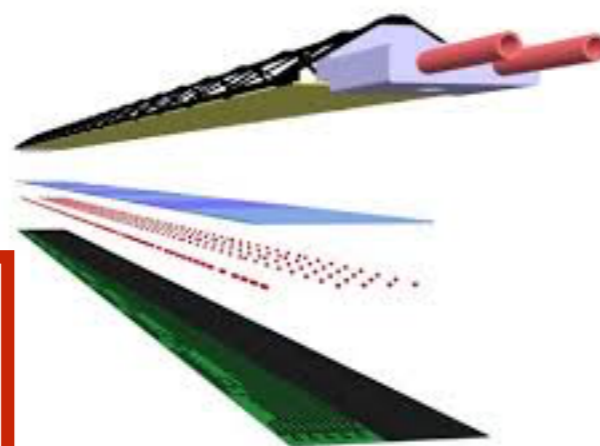
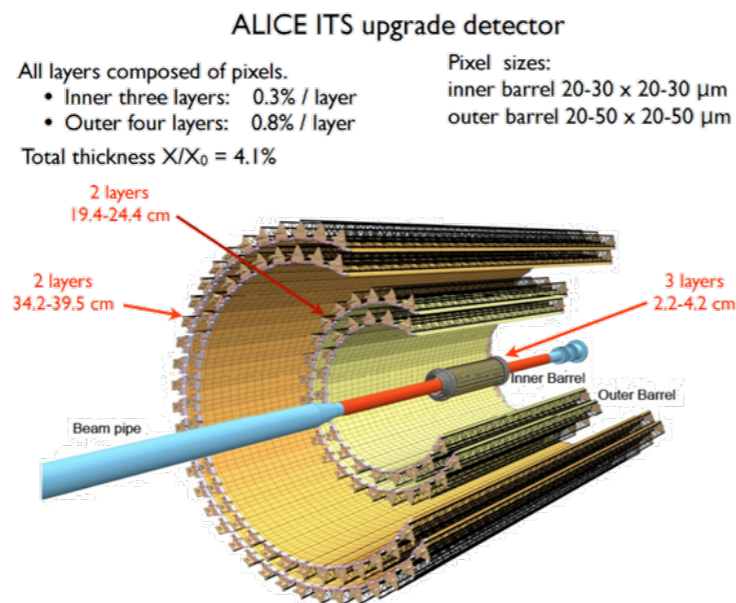
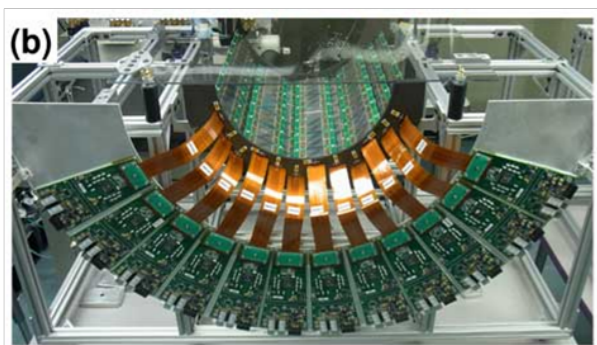


Matrix of tracking options

Inner tracker

Reuse PHENIX VTX Components

- Momentum Resolution Limited by Multiple Scattering.
- Significant Dead Area (non-working & gaps)



Attractive option:
Copy of ALICE ITS upgrade
3-layer inner barrel

Outer tracker

New PHENIX-like Components

- Straightforward technology.
- Fast (no event pileup).
- Multiple-Scat limited.
- Little PID capability



Compact TPC (ala ALICE?)

- Higher momentum resolution
- Smaller Bremsstrahlung tails.
- Leverage ALICE R&D
- PID via dE/dx & neutral V's.

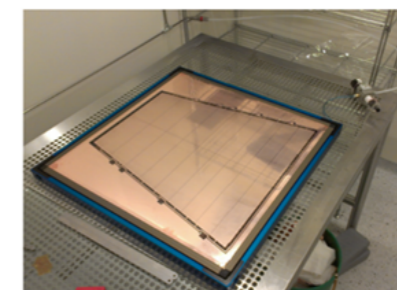
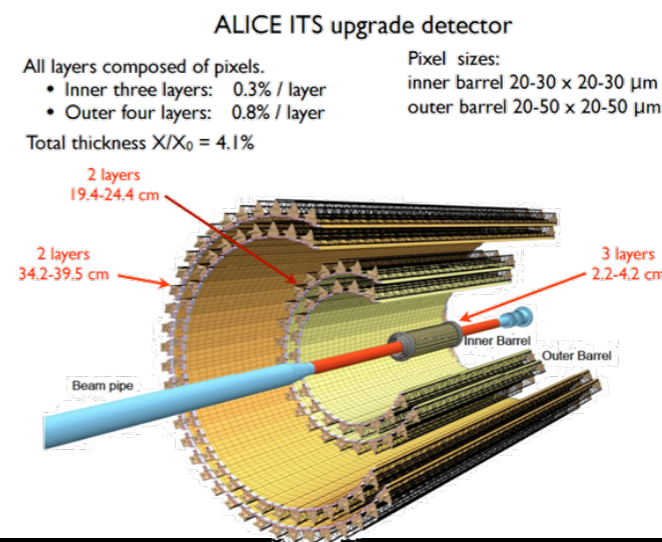
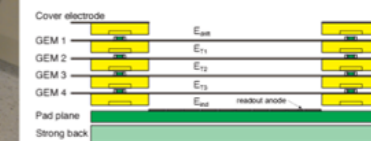
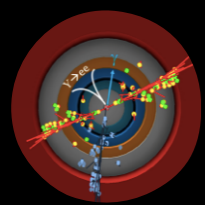
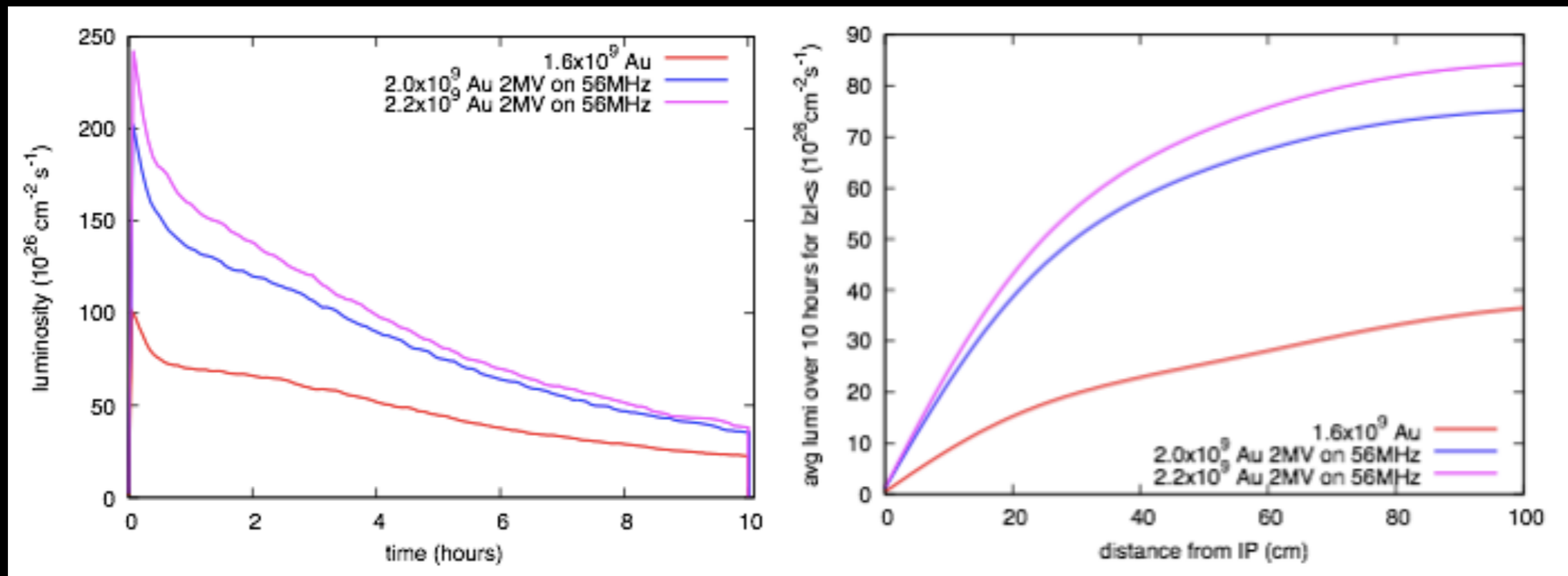


Figure 4.7: Photograph of an IRDC GEM foil in the stretching frame.



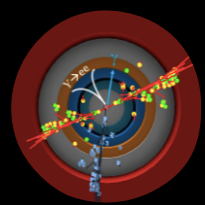


Au+Au luminosity projections from BNL Collider-Accelerator Department (2.5x RHIC Run-14 in $|z| < 10$ cm vertex cut)

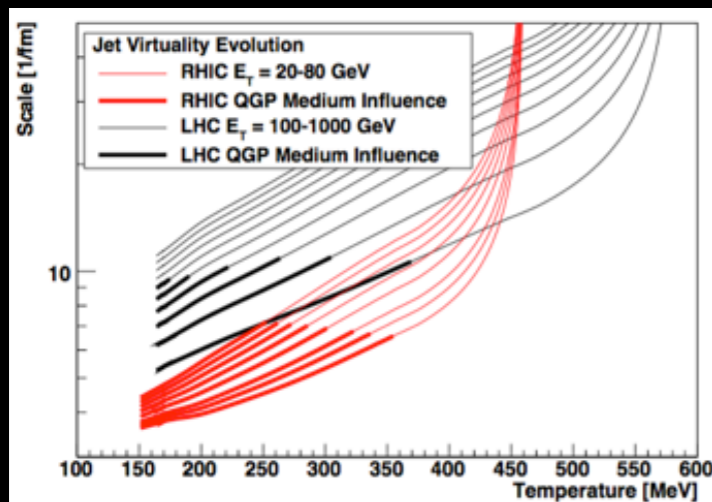


In nominal 1yr Au+Au run, 100 billion Au+Au min bias events within $|z| < 10$ cm (@15kHz)

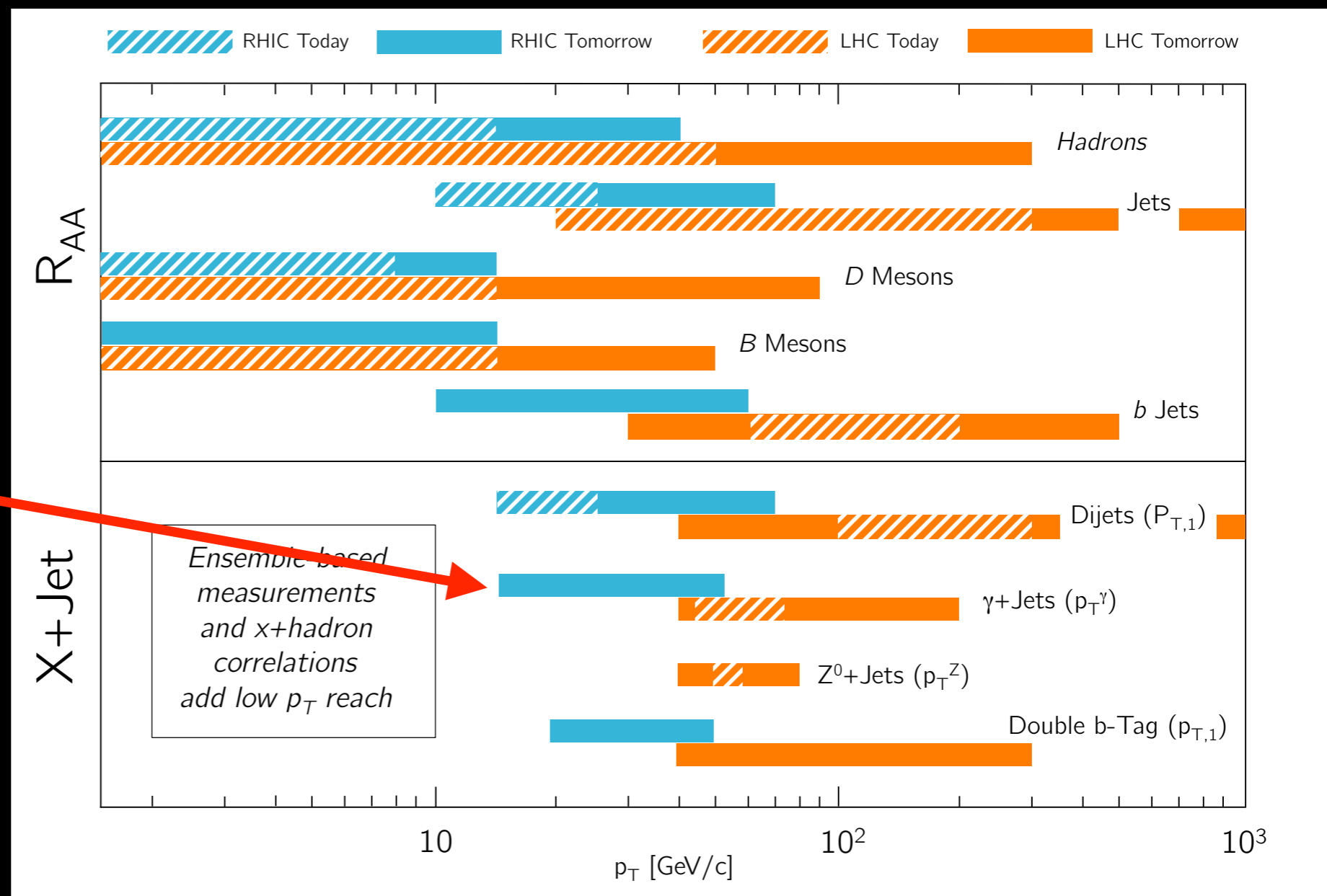
Rare triggers can be measured with calorimeters (i.e. wider z-vertex range): sample 0.6 trillion events.

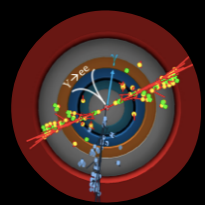


Kinematic overlap of future RHIC and LHC capabilities

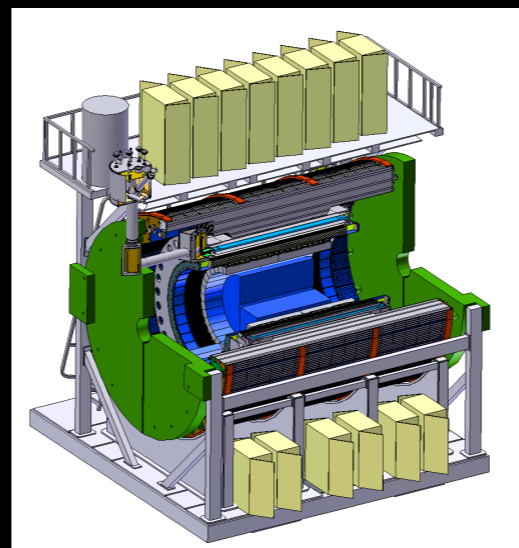
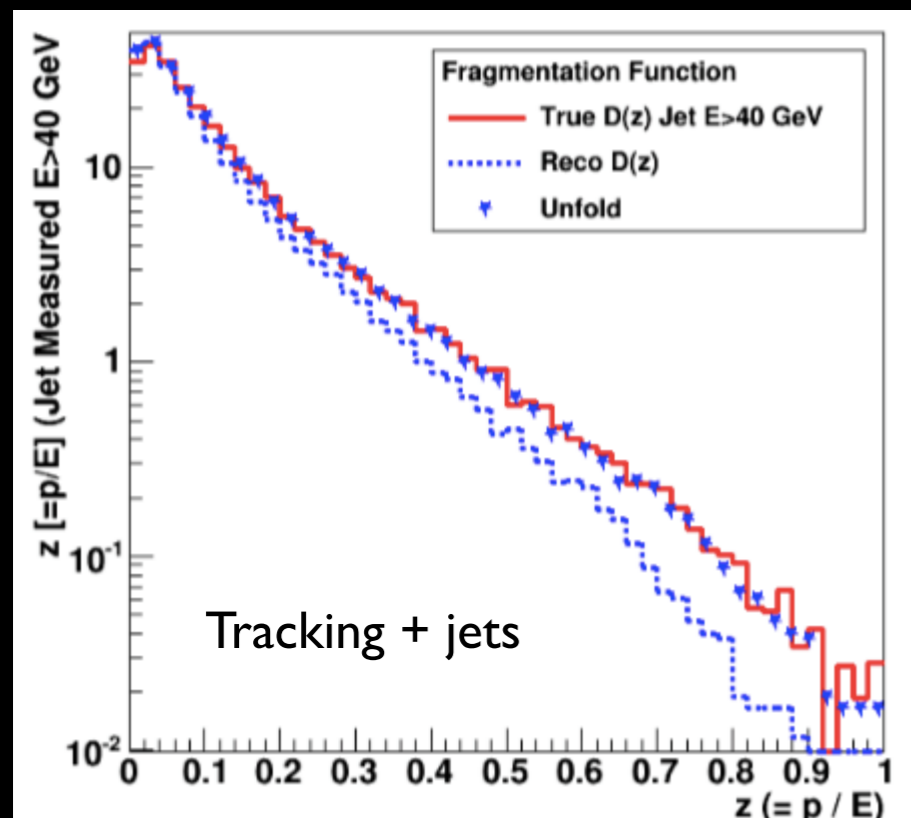


γ +jet



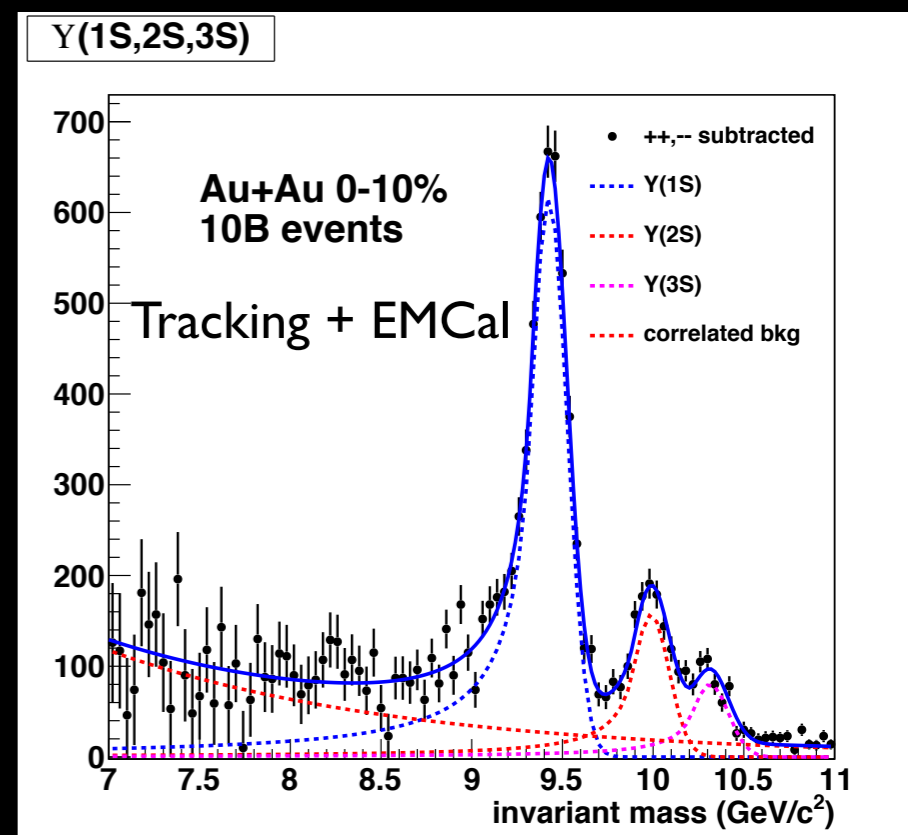


Jet fragmentation functions

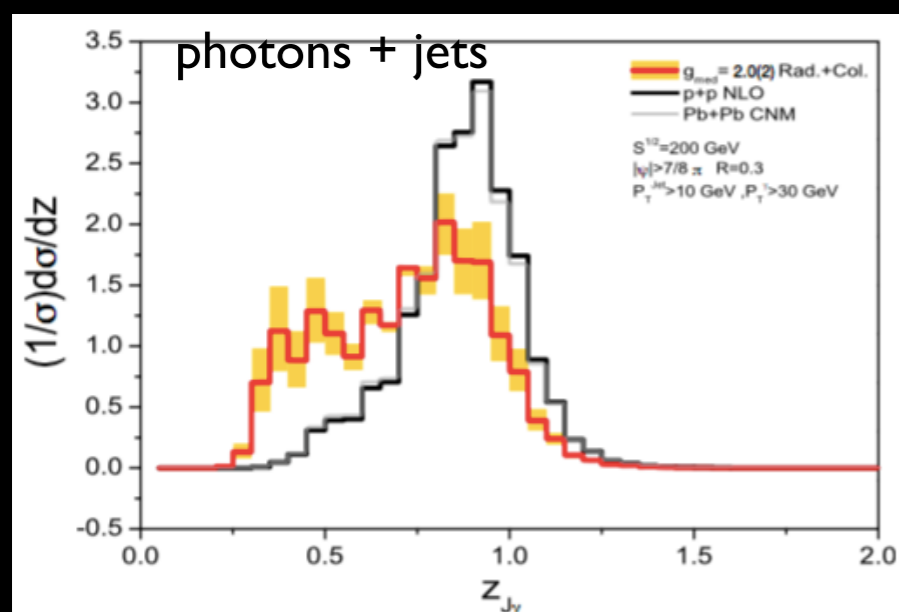


Mix and match tracking,
EMCal and HCal info

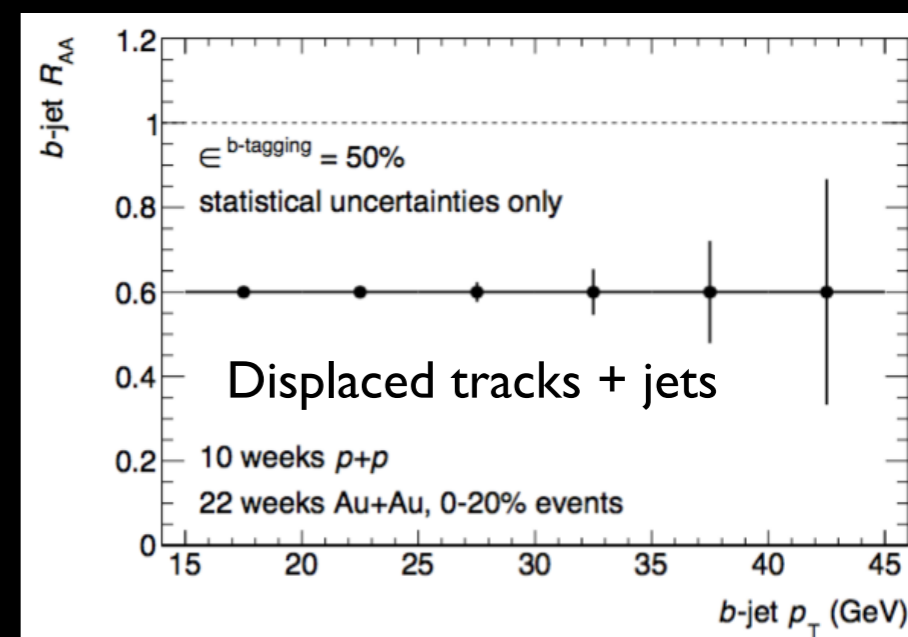
Upsilon spectroscopy

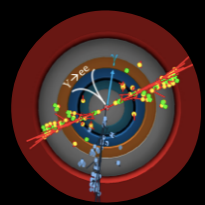


photon-jet correlations



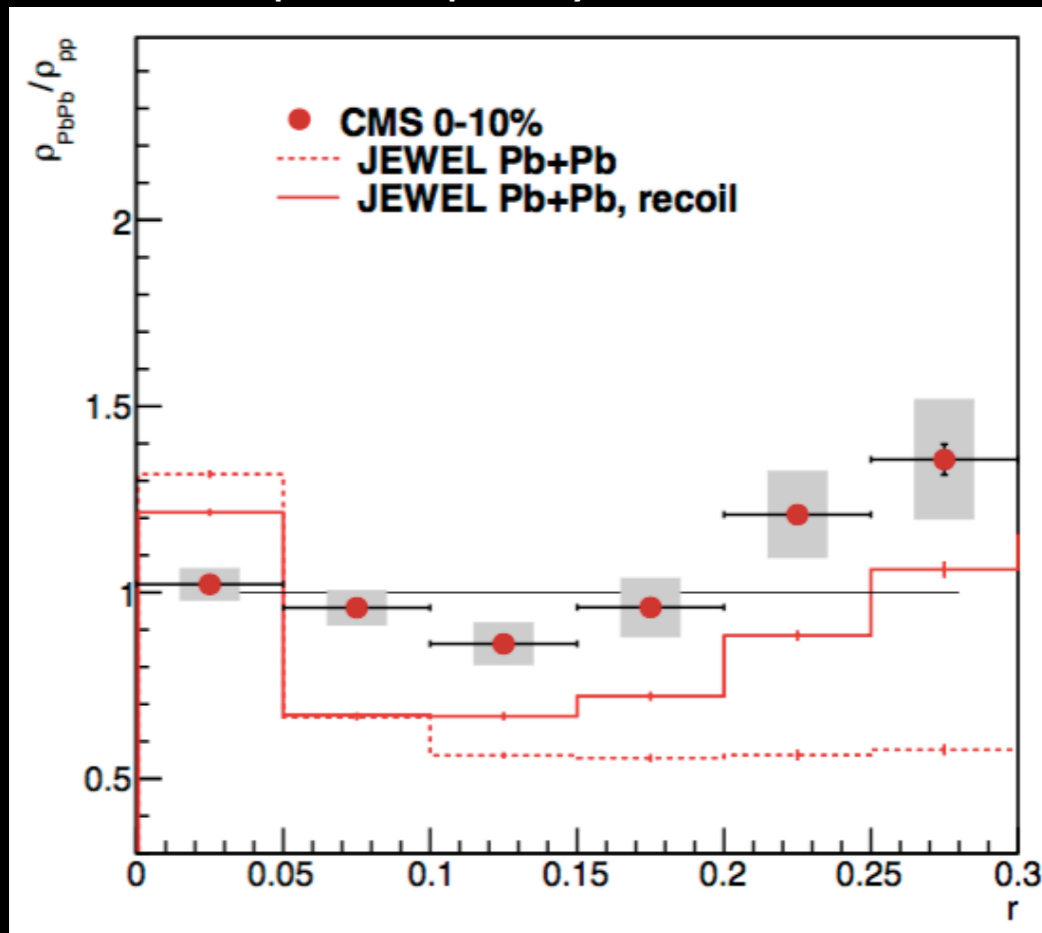
B-jet tagging



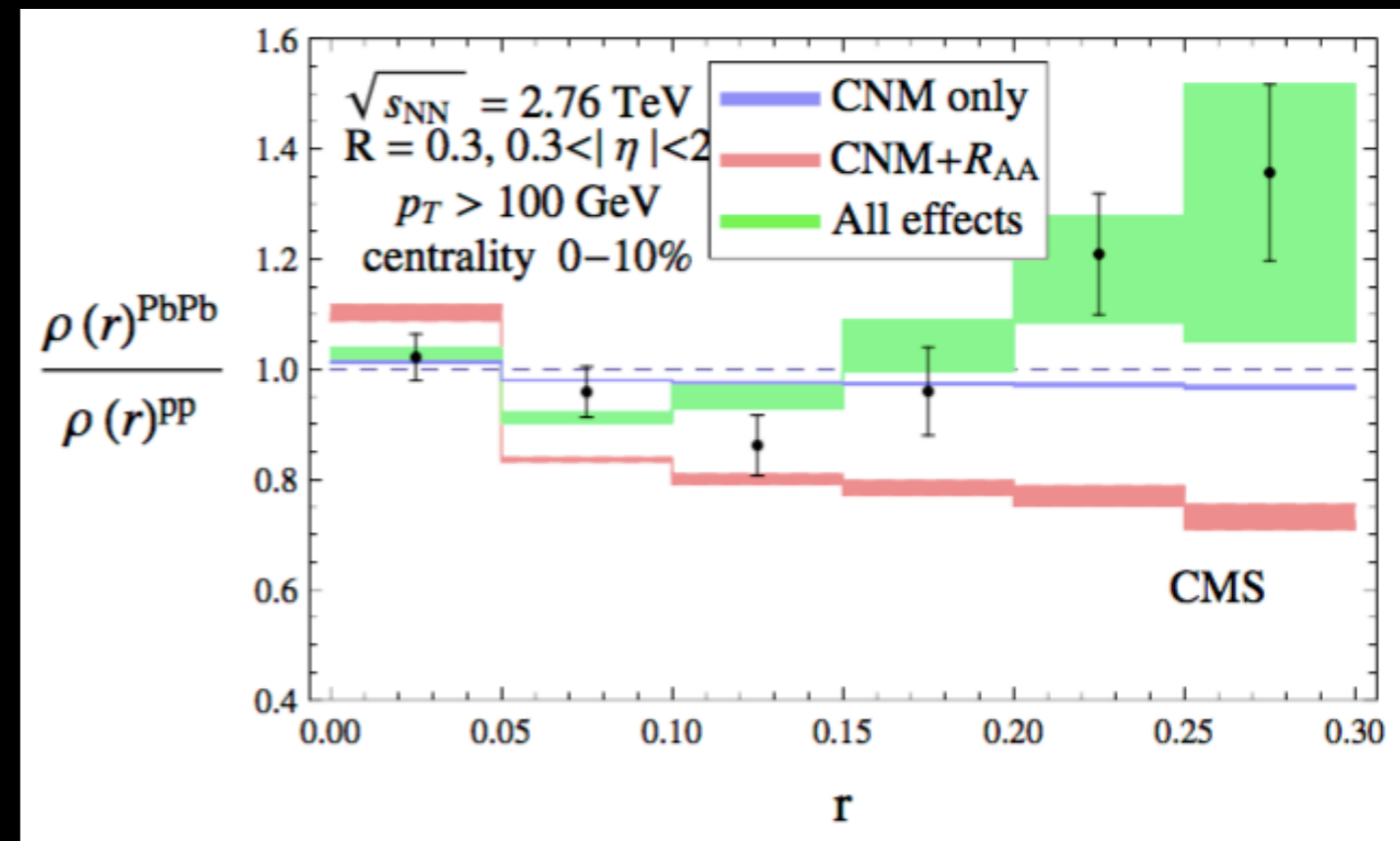


From data + theory to physics

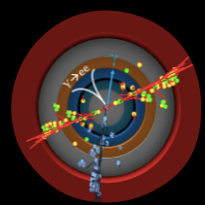
Comparison plot by van Leeuwen



Vitev, Kang et al



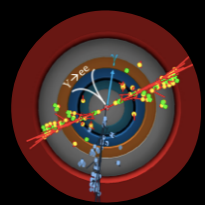
What are the meaningful questions?
Which *systematic* precision can we reach?



The Jet Energy-loss Tomography with a Statistical and Computationally Advanced Program Envelope (JETSCAPE) Collaboration

...jets provide powerful tools to study the internal structure of the plasma. However, interpretation of jet measurements requires sophisticated numerical modeling and simulation, and comparison of such theory calculations with experimental data demands advanced statistical tools. The JETSCAPE Collaboration is an interdisciplinary team of physicists, computer scientists, and statisticians developing a comprehensive software framework providing a systematic, rigorous approach to address this program. ...

The JETSCAPE Collaboration will develop a scalable and portable open source software package to replace a variety of existing codes. The modular integrated software framework will consist of interacting generators to simulate (i) wave functions of the incoming nuclei, (ii) viscous fluid dynamical evolution of the hot plasma, and (iii) transport and modification of jets in the plasma. Integrated advanced statistical analysis tools will provide non-expert users with quantitative methods to validate novel theoretical descriptions of such jet modification, by comparison with the complete set of current experimental data...



JETSCAPE

- PI's: Abhijit Majumder, Bass, Fries, Gale, Heinz, Jacak, Jacobs, Putschke, Roland, Schwiebert, Soltz, Wang, Wolpert
- Recommended for funding at NSF (\$3.6M total for postdocs, workshops etc over 4 yrs)
- Start date: June 2016?
- Experiments: Work on interface of simulations/analyses with JETSCAPE

Endgame of HI jet measurements in the next decade

- Comprehensive characterization of final jet constituent distribution
- Control over initial state using tags
- Requires overlap of kinematic and reconstruction capabilities at LHC and RHIC (\rightarrow sPHENIX)
- Requires major progress in jet calculations and theory/data interface (\rightarrow JETSCAPE,...)